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Journal of Sedimentary Petrology

JUL 20 1959

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

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REFLECTIONS ON THE INTERPRETATION OF HEAVY MINERAL ANALYSES[1]

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ABSTRACT

The study of heavy minerals, an important field of endeavor for the sedimentary petrographer prior to 1940, has declined in recent years. This decline, caused primarily by the disappointing results of heavy mineral correlation, is regrettable because in regional stratigraphic and paleogeographic research the method is capable of contributing important information concerning the location and character of source areas and the distribution patterns of sediments. The following factors can modify the heavy mineral composition and limit the interpretation of the assemblage in terms of source area conditions: (1) weathering, (2) abrasion, (3) selective sorting, and (4) post-depositional solution. This paper attempts to show that (3) and (4) are of minor importance. In basins with a low rate of sediment supply and under conditions of intense weathering and reworking the others can strongly modify the composition of the heavy mineral assemblage. In basins of rapid deposition deriving their sediment in general from source areas with active erosion, the influence of all factors is negligible and the heavy mineral assemblage directly reflects the petrography of the source area. An example illustrates the type of problem for which heavy mineral analysis is of value. Problems of sediment source and distribution in the Mississippi valley and the Gulf Coastal Plain in the Cenzoic are a field where heavy mineral analysis is considered rewarding.

The author, during the past ten years, has had the opportunity to carry out a number of regional heavy mineral studies. The investigations have included both work on Recent sediments and on the laws that control the composition of heavy mineral assemblages, and studies of the stratigraphy and paleogeography of ancient basins. Some general thoughts concerning the interpretation of heavy mineral assemblages, based in part on this work, were presented in a symposium "Problems of correlating and interpreting sedimentary facies" at the Los Angeles meeting of the American Association of Petroleum Geologists, March 1958. The present paper is a further elaboration of the author's thoughts on the subject in the hope of stimulating interest in a topic that in his opinion has been neglected too much in recent years, particularly in the United States. The author wishes to thank M. N. Bramlette, P. D. Krynine and G. A. Rusnak for stimulating discussions on the subject.

Heavy mineral analysis is almost the oldest field of endeavor in sedimentary petrology. As early as the end of the 19th century publications on the heavy mineral content of sediments were remarkably abundant. An interesting history of sedimentary petrology prior to 1930 was given by Boswell (1933) and is well worth reading. It shows the stages of growth from a collector's interest in an inventory of all heavy minerals in a sample on through qualitative analysis for stratigraphic and petrologic studies, for example tracing the erosional history of a batholith (Brammall, 1928), to modern quantitative techniques. In the following years, preceding World War II, economic interest from the side of the petroleum industry stimulated a period of great activity, primarily in the use of heavy mineral analysis as a correlation tool. This is demonstrated by an impressive series of publications and an even larger quantity of unpublished material in oil company files. Even today, heavy mineral analysis and heavy mineral correlation are synonymous to many geologists. Recently, however, the interest in investigations of this nature has declined rapidly, and one might even say that they have fallen into disrepute.

In part this is due to the development of much more sensitive and convenient techniques for correlation, as for example micropaleontology, electric log analysis and pollen studies. These methods which have many scientific and practical advantages have in most cases obviated the need for mineral-

[1] Manuscript received November 22, 1958.

ogical correlation. Only occasionally the method is still applied (Feo-Codecido 1956).

This, however, is not the only reason for the decrease in interest in the field. Mineral zones are often broad and poorly defined and have a disconcerting habit of crossing other markers at high angles. A good example is Cogen's study of the Gulf Coast Tertiary (1940). Unfortunately, geologists have rarely stopped to ask why heavy mineral zones behave in this peculiar way, but have discarded their use instead. It is the author's opinion that this attitude is not justified and that in modern geology the study of heavy minerals in sediments has a definite and important place. It is the purpose of the paper to argue in favor of this viewpoint.

In recent years the interest in broad regional studies of the paleogeography and facies distribution of entire depositional basins has increased enormously. Such studies are designed to provide detailed descriptions of the lithology of the basin and of its tectonic and depositional history. They have proved to be geologically rewarding and have considerable economic importance because they are useful for a better understanding of oil generation and migration. In order to obtain the sought-for understanding of the depositional history, such studies require information concerning the sources of sediments, the morphological, climatological and petrographical character of the source areas, and the distribution patterns of the detrital materials in the basin. In this respect the mineralogical analysis of both the light and heavy detrital fraction of the sediments is of great value. The unraveling of the complex erosional history of a sediment source and of shifts in drainage patterns by these means have been found helpful in many cases. Light minerals are most useful when the source area consists mainly of sedimentary or low rank metamorphic rocks, for example a mountain range in its earliest stage of uplift and erosion. Heavy mineral studies, on the other hand, are most useful when erosion has proceeded to deeper metamorphic and igneous rocks. Sometimes, with this method, both the erosional and tectonic history of the surrounding land mass and the depositional history of the basin have been worked out simultaneously (van Andel, 1958).

For such studies we must be able to interpret the mineral assemblages found in the sediments in terms of the characteristics of the source rock. This implies the ability to eliminate or take into account all modifications the assemblages undergo between the source rock and the completed analysis. The four principal factors that may modify the mineral composition are: (1) weathering both in the source area and in the depositional basin; (2) mechanical destruction during transportation; (3) selective sorting of minerals according to size and density, and (4) chemical destruction after deposition. A fifth factor, the error associated with the procedures of sampling and analysis, need not be considered here.

The importance of modifications of the heavy mineral assemblage by weathering has been discussed and emphasized by many authors. A recent discussion of the problem was provided by Weyl (1952a). The effect of weathering is shown by a decrease of the less stable components, as for example (in approximate order) augite, hornblende and epidote, and a corresponding relative increase of the stable elements, kyanite, staurolite, tourmaline, zircon, and rutile. In extreme cases this process can supposedly convert a hornblende-epidote association into a kyanite-staurolite-zircon assemblage (Weyl, 1949). Although there is difference of opinion between various authors concerning the order of decreasing stability (see Pettijohn, 1957, table 95) and the conditions under which weathering takes place, it appears to be a well established fact that heavy minerals can indeed be selectively eliminated by weathering.

For the purpose of this paper the processes of weathering themselves are of less interest than the quantitative importance of weathering as a destructive agent in controlling the mineral composition of sediments in depositional basins. Admitting that weathering can modify the heavy mineral assemblage in the source area or after deposition, how often does this actually happen and to what extent?

A survey of the literature shows that although many assumed cases of weathering of heavy mineral assemblages have been described, an appreciable portion of them

can be explained equally well as the result of mixing of sediments from various sources (van Andel, 1952). Of the remaining still impressive number of cases the most pronounced examples are found either in very permeable sands and gravels above the ground water table (see for example Weyl, 1951a), in intensely weathered podzolic soils in the temperate zone (e.g. Weyl, 1951b, van der Marel, 1949), or in areas under humid tropical conditions (Wahlstrom, 1948, Hübl, 1942, and others).

The detritus supplied from a source area, however, is not necessarily derived from the weathered crust. In tropical regions the thickness of the weathered crust can be great and the regolith can represent an appreciable quantity of sediment available for erosion. In temperate zones the thickness of the weathered crust is generally small and when erosion is sufficiently active to supply the large quantity of material required to fill a major depositional basin, fresh bedrock is generally exposed. In most rivers of the temperate zone weathered detritus appears to constitute a small part of the load only, but even in the tropics highly unstable mineral assemblages are often found in rivers draining deeply weathered areas (for example, New Guinea, van Rummelen, 1951; Guayana Shield, van Andel and Postma, 1954; Nile, Shukri, 1950). Krynine (1935) has shown that under conditions of severe tropical weathering arkoses can be formed. It may be noted in passing that the author is familiar with a number of comparisons of outcrop and subsurface samples from the same formation in tropical areas. No significant differences attributable to weathering have ever been observed.

Apparently, even conditions of intense weathering in the drainage basin of a river need not result in a stream of detritus which is devoid of or even deficient in unstable components. This is probably at least partly due to the fact that the dense vegetation in humid tropical areas restricts lateral erosion. There is emphasis on vertical erosion as soon as the relief is sufficiently pronounced to create rivers of enough competence to carry an abundance of sand-sized sediment and heavy minerals. Where relief is not great enough, the supply of sediment and consequently the rate of sedimentation in the basin will be very low.

This suggests that although weathering certainly may modify heavy mineral assemblages profoundly, its influence on the composition of sediments is negligible in basins with a moderate to rapid rate of deposition. On old cratons, weathering under tropical conditions may result in deep and complete alteration of the mineral assemblages. It is, however, a slow process, most active in areas of low relief, and its products will be important only in basins with a slow rate of deposition.

Another factor theoretically capable of modifying the composition of the heavy mineral assemblage is selective mechanical destruction during transportation. Laboratory experiments on the rates of wear of various mineral species show that there is considerable difference between different species in the susceptibility for wear (for a summary see Pettijohn, 1957, pp. 558–561). Studies of natural examples, however, have never demonstrated an appreciable effect of mechanical wear in rivers even with 600–1000 miles of transportation (Russell, 1939 for the Mississippi; van Andel, 1950 for the Rhine). Even for beaches where the total distance traveled by the particles may be many times greater than the distances attained in river transportation, no conclusive proof for the elimination or even reduction of minerals has been presented. Nevertheless, it can be assumed that very prolonged reworking may result in the destruction of the mechanically less stable elements, but the time and energy required are certainly very large.

The composition of the heavy mineral assemblage of a sediment can be modified by sorting according to density and size during transportation and deposition. Heavy minerals cover a wide range of densities from 2.89, the cutoff point in bromoform, to over 5.0. Sizes range from an approximate minimum of 0.03 mm to larger than 0.5 mm and many species show a preference for specific size ranges. Zircon and rutile, for example, are almost always very small. Consequently, very fine grained sediments tend to have assemblages rich in zircon (van Andel, 1954; Poole, 1958) which are the result of sorting, not of the presence of a zircon-rich source rock. A zircon assemblage, therefore,

always requires a test for dependence on sorting. The study of siltstones and shales in general has been found unrewarding.

Many other minerals have preferred size ranges, which in general depend upon the particular size distribution of that mineral in the source rock. Pyroxenes, especially those derived from volcanic extrusives, are often large, but in other cases there is no preferred range or the pyroxenes are small. Epidotes are frequently concentrated in the finer grade. In some cases it is possible to use the size distribution of a mineral species as a varietal characteristic (van Andel, 1950).

The effects of sorting can be strong, when the assemblage contains species of widely divergent preferred ranges. In general, the influence of size is predominant; the influence of density is of minor importance. In the region of the Rhone delta, France, two heavy mineral associations occur; a pyroxene-hornblende-epidote assemblage in the delta and nearshore zone, and a hornblende-epidote assemblage in the offshore deposits. The source of the deltaic assemblage can be traced easily to the volcanics of the French Central Massif (pyroxene) and the French and Swiss Alps (hornblende and epidote). The source of the other assemblage is obscure, since lateral supply appears to be ruled out by the presence of very different assemblages on both sides of the delta along the coast of the Mediterranean (van Andel, 1956).

The analysis of the grain size distributions of the diagnostic minerals (which together make up more than 75 percent of the assemblages) shows that the pyroxenes are restricted to the coarsest fraction, the epidote to the finest, and the hornblende occupies an intermediate position (fig. 1). The three minerals have approximately the same density. Differentiation of this assemblage by size sorting will result in coarse lag deposits rich in pyroxene and fine differentiates with abundant epidote. A plot of all analyses from this region in terms of a three-mineral system, pyroxene-hornblende-epidote, shows a clear differentiation series starting from the average Rhone assemblage The series is closely related to the depositional facies of the samples (fig. 2). The deltaic deposits are mainly coarse grained, lag-type, beach, dune and river sands; the offshore sediments in general are fine grained end products of the sorting process. The regional distribution of heavy mineral associations apparently is not due to differences in source, but is the result of sorting of a highly heterogeneous original assemblage. It is clear that failure to recognize this situation in an ancient basin would result in completely erroneous conclusions concerning the location and character of sediment sources.

This example has been described at some length because it presents an unusually clear case of an often mentioned phenomenon. Fortunately, such cases are by no means common. The Mississippi delta, for example, shows no differences in mineral composition at all between sandy and clayey deposits. In fact, the heavy mineral assemblages in the entire Mississippi distributive province are strikingly homogeneous. Thus, while a test of grain size control is always necessary, it may be concluded that only rarely will this factor seriously impair the interpretation of heavy mineral distributions in terms of source areas and source area characteristics.

The last point requiring discussion is the post-depositional destruction of minerals, a process which Pettijohn (1941) has called intrastratal solution. This process can be taken to include both weathering at the site of deposition and solution occurring at greater depth below the water table, but for the present discussion the author prefers to restrict its meaning to the latter process.

There is no doubt that the process of intrastratal solution does indeed exist. Several well documented examples can be found in the literature (Bramlette, 1941; Weyl, 1952b) of cemented or concretionary parts of sandstones with a mineral assemblage much richer in unstable components than the surrounding rock. Since differences in source between the various parts of the same sand could be ruled out, intrastratal solution must be held responsible for the disappearance of the less stable minerals from the porous non-cemented parts of the deposit. The number of such cases is small, and as far as this author is aware no proof has ever been advanced that the process can also operate on a much larger scale involving

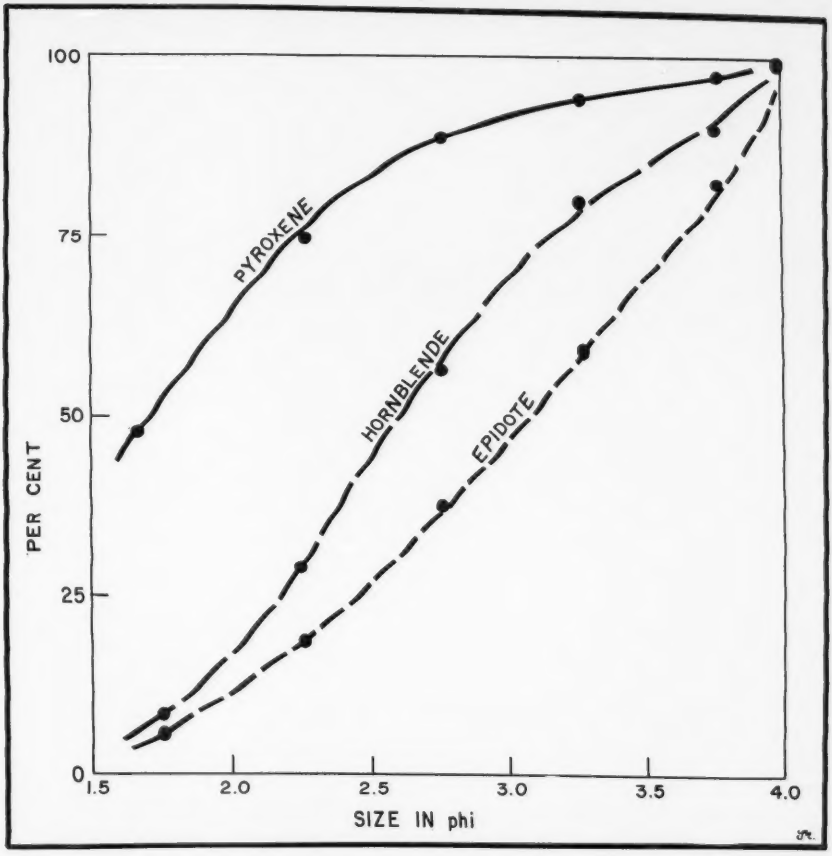

FIG. 1.—Cumulative grain size distributions of principal minerals pyroxene, hornblende and epidote in detritus supplied by the river Rhone. Data from table 6, van Andel, 1956.

great thicknesses and expanses of sediment.

Sediment sources are infinitely varied in mineralogical composition and any number of source rocks can contribute minerals to the depositional basin. Theoretically, the variety of possible heavy mineral assemblages is infinite. Nevertheless, the number of assemblages that usually is found is astonishingly small. Listing only the most important constituents the more common assemblages are the hornblende-epidote, epidote, kyanite-zircon, staurolite-zircon, garnet-zircon-tourmaline and zircon-tourmaline associations.

In many sedimentary basins these associations follow each other in a specific order which is from young to old, the one indicated above. Examples of such systematic sequences are found in the Alpine geosyncline (von Moos, 1935), Tunesia, Gulf of Mexico (Cogen, 1940), New Guinea, Java (Doeglas, 1940), Bighorn Basin (Stow, 1938), and Western Venezuela. The sequence generally occurs in Upper Cretaceous to Quaternary sediments. In pre-Cretaceous rocks the unstable minerals are rare and the dominant minerals are zircon, tourmaline and sometimes garnet.

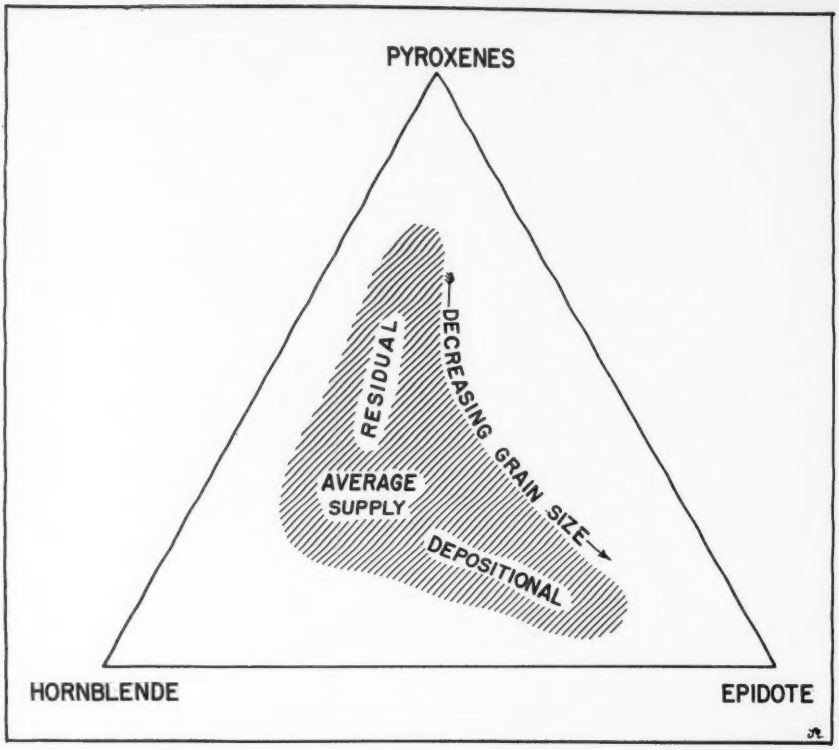

FIG. 2.—Triangle diagram of differentiation by sorting in the Rhone delta and offshore shelf of the heavy mineral assemblage supplied by the river Rhone: from fig. 16, van Andel, 1956.

Pettijohn (1941; 1957, p. 503–506, 514–520, 674–679) has discussed this phenomenon at length with the aid of a compilation of all published heavy mineral analysis. This compilation clearly demonstrates a general decrease of the richness of the suite with increasing age and an increase of the abundance of stable minerals. This persistence series of the individual minerals and the sequence of heavy mineral assemblages mentioned above are quite similar to the mineral stability series proposed by several authors (Pettijohn, 1957, table 95). The consideration of this and related facts has led Pettijohn to conclude that "it is possible, if not probable, that the older sediments have lost the less stable species by intrastratal solution" and that "the suggestion has been made that the heavy mineral zones are stability zones and owe their existence and character to selective removal of the less stable species in the deeper zones by intrastratal solution" (Pettijohn, 1957, p. 676–677). This is a statement of considerable importance because, if intrastratal solution does indeed have the importance suggested, most stratigraphic and paleogeographic conclusions based upon heavy mineral evidence would have no meaning.

Krynine (1942) has taken exception to such a wide application of the concept of intrastratal solution and has attributed the differences between heavy mineral zones to tectonic control through differences in source area petrography, morphology and weathering. His opinion has been ignored almost

completely and the question deserves re-examination.

In this respect three sets of observations are of prime importance. The characteristic sequence of heavy mineral zones described above does not occur in all types of depositional basins but seems to be restricted to geosynclines. The more unstable members of the sequence appear during what Krynine (1942) has called the post-geosynclinal (orogenetic phase) and are the erosion products of the recently deformed and elevated mountain range. The unstable suites characterize foredeep ("molasse") deposits and the source areas are of the alpine type. Their first appearance, can, in many cases, be correlated quite closely with the phase of maximum diastrophism (van Andel, 1952) and the often stressed correlation between the heavy mineral zones and the geological time scale is true only in a very generalized sense. The epidote zone, for example, is of Pliocene age in New Guinea, Upper Oligocene-Miocene in Tunesia, Upper Oligocene in the alpine foredeep in Bavaria, Upper Eocene in Northwest Europe, Lower Oligocene in the sediments associated with the Andean foredeep in Western Venezuela. This suggests that diastrophism in the source area rather than mineral stability and intrastratal solution control the succession of zones, and that the minerals reflect the successive appearance by progressive uplift and erosion, of deeper metamorphic and igneous layers in the orogen.

If intrastratal solution would indeed be a major cause in the formation of heavy mineral zones, this should show at higher levels in an increase of corrosion structures before the final disappearance of the species. Such corrosion structures are easily observed (Edelman and Doeglas, 1932). For a number of unstable mineral zones in various parts of the world the author has investigated this possibility but has not observed any examples (van Andel, 1952). Similarly, it has been found impossible to establish a correlation between mineral stability and formation properties that would promote mineral solution as for example permeability and porosity.

The strongest argument in favor of the theory that heavy mineral zones are controlled by mineral stability rather than by provenance is that published analyses from many formations and many parts of the world show that unstable assemblages are indeed very rare in deposits of pre-Cretaceous time. However, it is very questionable whether a compilation of all published material, such as the one presented by Pettijohn (1941) in evidence of his intrastratal solution theory, is indeed reasonably representative for the heavy mineral suites of all rocks and facies of the geological column. A survey of the literature rather indicates the opposite. The Tertiary and Quaternary sediments that have been investigated for heavy minerals are predominantly of geosynclinal and foredeep facies and the less stable assemblages appear to be associated in general with orogenetic sources. Most of these studies have been carried out outside the United States, many of them in connection with unpublished petroleum exploration work. On the other hand, published information on the heavy minerals of pre-Cretaceous sediments is largely restricted to sediments in platform facies that were derived from cratonic sources. Much of this work was done in the United States. Geosynclinal deposits of pre-Cretaceous age are quite common, but those belonging to the post-orogenetic stage of development of the geosyncline have rarely been preserved and their heavy minerals have seldom been studied. Thus, it appears that the sample represented by the heavy mineral literature is heavily biased; in favor of geosynclinal post-orogenetic sediments for the Cenozoic, in favor of stable platform deposits for the pre-Cretaceous.

Based upon these considerations the author feels that much can be said for the following interpretation of heavy mineral zones, which follows Krynine and is different in emphasis from the one favored by Pettijohn. In a stable platform environment, where the sediments are derived from a cratonic, deeply weathered source of low relief, mineral assemblages subjected to considerable reworking are strongly altered and in general stable, except in the immediate vicinity of fresh outcrops of igneous and metamorphic rock. The absence of unstable minerals appears to be due not to intrastratal solution but to processes prior to deep burial. On the other hand, in geosynclinal

and foredeep environments the mineral assemblage is essentially preserved in the composition inherited from the source area and the succession of mineral zones in such a basin reflects the formation, uplift and erosion of successively more complex rocks in the source area. Pronounced relief and rapid erosion in the source area with rapid burial in the depositional basin do not leave time for large scale elimination of unstable elements. The upward sequence of mineral zones reflects in inverse order the sequence: weathered layer—sedimentary and low rank metamorphics—high rank metamorphics and igneous, in the source areas. Numerous published studies of the heavy minerals of igneous and metamorphic rocks and, in particular, recent analyses by Fuechtbauer (oral communication) of the heavy mineral composition of conglomerates in the alpine foredeep in Bavaria demonstrate that the well known sequence of mineral zones can be explained completely in terms of the rocks available for erosion in the source area.

Consequently, the author is inclined to assign a minor role to intrastratal solution as a factor in the alteration of mineral assemblages. Heavy mineral assemblages can be altered profoundly if severe conditions and enough time are available, but this alteration appears to be a surface rather than a subsurface effect.

If this assumption is correct, then pre-Cretaceous series of geosynclinal sediments should possess the same sequence of stable and unstable associations found in many basins in the Tertiary, provided the post-orogenetic stage is included. Not many such complete series have been investigated. Recently, however, Sarkissian (1949, 1958) has published an extensive study of the geosynclinal deposits of Permian and Triassic age associated with the pre-Urals orogeny in Russia. His study shows that the post-orogenetic sediments carry the same highly unstable suites characteristic for Tertiary sediments of the same facies and thus form a strong argument in favor of the hypothesis developed here. His results have been summarized in table 1.

Several interesting examples of the use of heavy minerals for the interpretation of the geological and paleogeographical history of a basin have been published recently. The key to this type of study is a regional concept of heavy mineral distribution. In 1933 Edelman (quoted from Doeglas 1940) has defined the *sedimentary petrological province* as follows: "A sedimentary petrological province is a complex of sediments which by their geographical distribution, age and origin form a natural unit." The concept was originally derived from Baturin's work in the Caucasus. The application of this concept requires a regional and stratigraphic study of samples and puts much weight on a careful analysis of the interfingering and mixing of adjacent provinces and the features of provincial succession with time. Good examples of this method have been presented by Doeglas (1940) and by Cogen (1940). Much importance is attached to the regional approach and to the study of large

TABLE 1.—*Heavy mineral zones in the pre-Urals foredeep (after Sarkissian)*

Age		Region from north to south		
		Bashkir	Orenburg	Emba
TRIASSSIC		actinolite-glauconite	epidote	epidote
Upper Permian	U. Tartar L. Tartar	actinolite-glaucophane garnet-tremolite-hornblende	hornblende	kyanite-staurolite (epidote)
	U. Ufa	hornblende-pyroxene garnet epidote	stable	stable
	L. Ufa	stable		

numbers of samples with a wide coverage both in time and space.

This regional province concept has proved to be extremely fruitful in a large number of heavy mineral studies both of recent and ancient sediments of entire basins. It has, however, found little attention in the United States, where limited studies of a few samples in a localized area predominate in the literature.

An excellent example of the value of regional heavy mineral analysis for the paleogeography and geological history of a basin has recently been provided by Fuechtbauer (1953, 1958) in a study of the sources and distribution of sediments in the Oligocene-Miocene Molasse foredeep of the Alps in Bavaria. The deposits in this basin were largely derived from the mountain front in the south which, in the period investigated, had just passed through a major stage of deformation and uplift. The Middle Oligocene sediments of the basin all carry garnet assemblages derived from the south. By means of accessory minerals in the assemblages the various points can be identified from which the streams of sediment issued. Sediment distribution patterns are predominantly radial in great fans. In the Upper Oligocene the individual character of the various sources becomes more apparent and the distributive province at the far western end of the basin develops strongly. From this point of entrance a garnet-epidote association gradually spreads throughout the basin. The radial distribution pattern is replaced by an axial pattern with the development of an easterly regional dip. Gradually also the composition of the sediment changes and the garnet-epidote assemblage changes to an epidote assemblage. That this is the result of progressive erosion in the source area is shown by the analysis of heavy minerals in the accompanying conglomerates. A small contribution from the northeast is shown by the presence of a hornblende-containing assemblage in that part of the basin. Finally, during the upper Middle Miocene the eastward regional dip decreases and the sediment distribution pattern again becomes radial with fans spreading from various points along the southern margin of the basin. Schematically, the heavy mineral distributions and their changes with time have been indicated in figure 3 adapted from Fuechtbauer (1954).

Studies like the one just mentioned are based on large numbers of samples and a carefully established stratigraphic network. Given those prerequisites, however, they may greatly increase our understanding of sedimentation in a basin and consequently of its depositional history. It seems to the author that many problems in regional geology in the United States might well be fertile ground for regional heavy mineral study, and that the present lack of interest in the method, though understandable in view of the failure of so much localized work, is not justified. In conclusion one such problem that is of considerable importance and may be solved at least in part by mineralogical analysis may be described briefly.

This is the problem of the sources and history of the sediment supply for the Gulf of Mexico. After the early studies by Cogen (1940), Bornhauser (1940), and Goldstein (1942) no investigations of the sources of sediments, both ancient and modern, in this area have appeared. Cogen has shown that in this basin the same sequence of stable and unstable associations is found that has been described earlier in this paper. The youngest deposits investigated are Pliocene in age and contain an epidote assemblage with some hornblende. Information for the larger part of the Pleistocene is lacking until we come to the early Recent and Recent sediments which have complex sources. The modern Mississippi distributive province has a hornblende-pyroxene association. The source of these modern Mississippi sediments seems to be largely in the glacial deposits in its upper drainage basin. Horberg, in a series of studies, has shown that the early Pleistocene Upper Mississippi probably did not drain towards the Gulf of Mexico at all; and Potter (1955) has demonstrated that the Pliocene and early Pleistocene terrace deposits in Missouri and southern Illinois did not contain a modern Mississippi assemblage, but rather, exclusively locally-derived stable minerals. Potter considers that this assemblage is not the result of intensive weathering of an originally hornblende carrying suite. This reveals two interesting problems: (1) where did the Pliocene hornblende in the Gulf of Mexico come from if there was

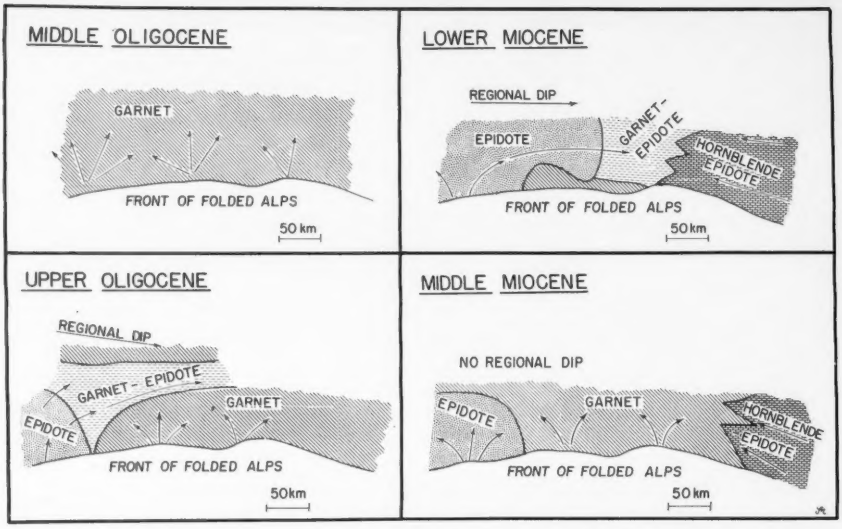

FIG. 3.—Regional distribution of heavy mineral associations in the Molasse foredeep, Bavaria, Germany. Simplified after Fuechtbauer, 1954, fig. 2.

no hornblende supplied through the Mississippi valley, and (2) when did the present Mississippi assemblage come into being and what is the history of its distribution? It may be added that the situation is further complicated by the fact that in the few samples of Pleistocene Mississippi valley deposits that have been investigated, a hornblende assemblage occurs which is quite similar to the present Mississippi association but without the pyroxene.

Thus it seems that a regional study of the Pliocene and Pleistocene sediments of the Mississippi and Gulf Coast region can be expected to throw considerable light upon the regional development of sedimentation in that area. The present paper must be seen as an attempt to encourage sedimentary petrologists to undertake this and other similar problems. There is no doubt in the author's mind that this would be found rewarding.

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FIGS. 1–6, JUNE, 1959

MICROFACIES OF WABASH REEF, WABASH, INDIANA[1]

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ABSTRACT

The microscopic statistical investigation of the Wabash reef has revealed five main microfacies ranging, in decreasing relative depth conditions, from highly dolomitic shales of the country-rock to dolomitic biocalcarenites and bioconstructed dolomitic limestones or dolomites belonging to the reef system. Among the microscopic parameters, the variation of the orientation of siliceous monoaxonic sponge spicules in the shales can be used as a criterion for predicting the position of the reef.

INTRODUCTION

The particular structure with which this investigation deals is designated in the literature as the Wabash Dome and has been studied in various degrees by several early workers of Indiana. Cummings and Shrock (1926, 1928) performed the most detailed investigation and are credited with presenting sufficient evidence to prove that the dome-like structure was a reef composed of three distinct zones: the massive core of colonial organisms, inclined beds dipping radially away from the core and composed of organic core-derived fragments, and the normal inter-reef stratigraphic sequence containing a fauna different from that of the reef. The early studies included only macroscopic features, but some microscopic paleontological work has recently been done by Lowenstam (1949, 1950).

LOCATION

The area of study is located $SE\frac{1}{4}$ $SE\frac{1}{4}$ of section 11, R. 6 E., T. 27 N., of the Wabash quadrangle, Wabash County, Indiana. The reef is situated just north of the Big Four railroad station in the city of Wabash. It is cut from flank to flank exactly through its center by a railroad cut exposing about 800 feet of reef structure of which 250 feet is unstratified core. The cut is up to 55 feet deep but neither the top nor the bottom of the reef is visible, the top being removed by erosion and the bottom being below the level of the tracks (fig. 1).

[1] This is the first of a series of contributions to the petrography of Silurian and Devonian reefs of the northern midwest presently undertaken by the senior author and his co-workers. Manuscript received December 18, 1958.

PURPOSE AND METHOD OF STUDY

The purpose of the present study was to determine the reciprocal relations between a Silurian reef structure and its surrounding sediment. The investigation included an integration of field observations with a series of 213 thin sections cut perpendicular to the bedding which were collected at one foot intervals from ten vertical sections located in various parts of the reef and off-reef shales (fig. 1). Each thin section, regardless of its location, was classified in a specific microfacies on the basis of organism content and microscopic texture. Statistical counts were then made of several microscopic parameters including the clasticity and frequency of detrital minerals and transported organisms and the degree of dolomitization. Variation in these observable compositional elements reflected changes in sedimentary conditions during reef growth. These variations showed that different bathymetric and mechanical conditions such as depth, turbulence, and agitation existed in various parts of the reef and adjacent country rock during reef development. Outcrop and thin section study reveals that these conditions varied both in space, displayed by differences in adjacent stratigraphically equivalent units, and in time, by differences in superposed units in a vertical section.

DESCRIPTION OF MICROFACIES

Five distinct microfacies could be distinguished (fig. 2), each having a particular texture and fossil content representing a specific combination of sedimentary conditions. A description of these microfacies follows.

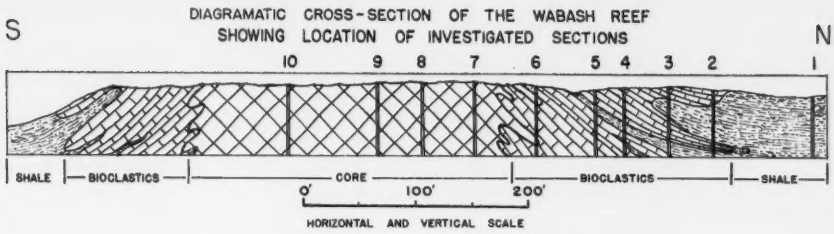

FIG. 1.—Diagrammatic cross-section of Wabash reef.

Microfacies 1.—Highly dolomitic shale with small scattered rhombohedra of dolomite. There is a complete absence of transported organic fragments, but sponge spicules are abundant and oriented parallel to the bedding. Quartz grains are relatively large and very numerous; small pyrite grains are also very widespread.

Microfacies 2.—Highly dolomitic shale with many small, irregularly-shaped, re-

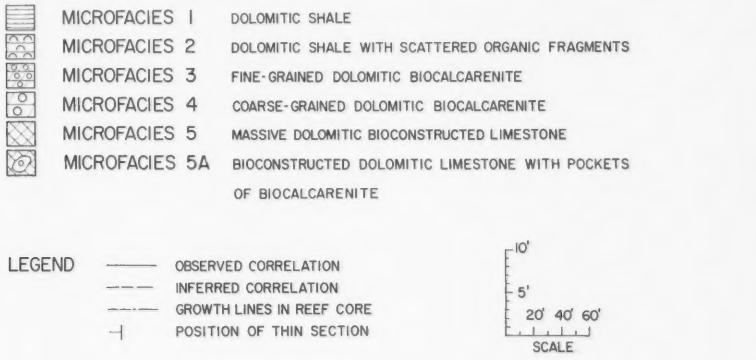

FIG. 2.—Microfacies correlation of investigated sections.

crystallized organic fragments. Sponge spicules are still abundant but less oriented with respect to the bedding. Quartz grains are somewhat smaller and less abundant.

Microfacies 3.—Fine-grained dolomitic biocalcarenite to biocalcarenitic dolomite nearly entirely composed of organic fragments in a cement of small dolomite rhombohedra and scattered clay minerals. Very few, completely unoriented, sponge spicules are present. Pyrite is much less abundant. Quartz shows a marked decrease in size and frequency.

Microfacies 4.—Coarse-grained dolomitic biocalcarenite to biocalcarenitic dolomite composed entirely of organic fragments derived from the core. The cement is a fine-grained mosaic of either anhedral crystals or rhombohedra of dolomite. There is a complete absence of spicules. Pyrite is more scattered, smaller grained, and anhedral. Quartz shows a decrease in size and frequency.

Microfacies 5.—Massive and recrystallized dolomitic bioconstructed limestone to bioconstructed dolomite (reef core) composed of massive Stromatoporoids and other colonial organisms. Sponge spicules are also absent. Pyrite is in the form of fine grains with diminished frequency. Quartz grains are small and scarce.

Microfacies 5A.—Same as microfacies 5 but with pockets of fine-grained dolomitic biocalcarenite. Pyrite is scarce; quartz grains vary greatly in frequency and may reach sizes similar to those in microfacies 1.

METHODS OF INVESTIGATION

Microscopic examination of the thin sections included the measurement of the maximum apparent diameter (or clasticity index) of detrital quartz and transported fossil fragments (Carozzi, 1950, 1958). This was found by computing the maximum diameter of the largest particle in a minimum of 100 grains, and frequency of detrital quartz, pyrite crystals, fossil fragments and monoaxonic, siliceous, sponge spicules. The frequency measurement corresponds to the absolute number of grains of a given mineral or of fragments of a given transported organism occurring over a constant area of the slide. For reliable results, the area of measurement should be chosen so that at least 100 grains can be counted. For the quartz, the area corresponded to two randomly selected fields of 3 sq. mm, for the organic fragments and the pyrite crystals 6 similar fields were used, and for the sponge spicules three fields were investigated.

The percentage of dolomite of the total carbonate present was calculated by an X-ray diffraction method described by Tennant and Berger (1957). Several staining techniques were attempted on both the uncovered thin section and polished samples to distinguish calcite from dolomite, but none yielded results that were satisfactory for both the coarsely recrystallized core and the fine-grained shales. The diffraction method was used by calculating the relative intensities of the strongest power diffraction peak for calcite and dolomite and comparing these ratios to peaks obtained from known percentages of these minerals. Eleven mixtures were prepared, one of pure calcite, one of pure dolomite, and the remainder at 10 per cent intervals between the pure end-members. The mixtures were X-rayed and, from the various intensities of the peaks, a reference chart was prepared calibrating the calcite/dolomite intensity ratio against known percentages of dolomite. This graph served as a reference system for the unknown field samples. Field samples generally contained calcite veins or pockets and to obtain a representative sample of each specimen, several chips, randomly selected, were ground in a hand mortar. Chips were ground for four minutes to insure uniform grain size and the powder was placed in labeled, sealed bottles to prevent hydration.

The copper X-ray tube diffractometer was permitted to rotate through an angle (2θ) that would include the main calcite and dolomite peaks which occur at 29.39° and 30.96° respectively.

Minor errors introduced into this calculation were due to nonuniformity of the grain size of the carbonate powder, breakage of the carbonates along preferred directions due to cleavage, and packing of the powder in the holders that were mounted in the diffractometer. Despite limitations, X-raying several field samples three times (each) showed that percentages were correct to about 4 per cent, indicating sufficient reliability for the purpose of this study.

On the diagrams (figs. 3 and 4) arithmetic scales were used for clasticity values and degrees of dolomitization and logarithmic scales for frequency values because of their high magnitudes.

DESCRIPTION OF THE SECTIONS

Section 1 (fig. 3) is about 70 feet north of the reef structure in the Mississinewa Shale. Clasticity and frequency of quartz have parallel values and are the largest of all the investigated sections. Sponge spicules oriented parallel to the bedding are abundant. Reef-derived fossil fragments are entirely absent.

Section 2 (fig. 3) is located directly at the north margin of the reef where samples include shale as well as dolomitic biocalcarenites. Quartz, pyrite and oriented spicules are abundant. Colonial organism fragments of small dimensions appear in most of the samples.

Section 3 (fig. 3) in the fine-grained biocalcarenites of low dip shows a slight decrease in quartz and pyrite content with an increase in the size and abundance of organic fragments. Spicules are less numerous and unoriented.

Sections 4 and 5 (fig. 3) are located in the steeply dipping, coarse biocalcarenites. Quartz and pyrite show a progressive decrease in abundance. Spicules are nearly absent. Organic fragments show a substantial increase in clasticity and frequency.

Section 6 (fig. 3), located at the north margin of the reef core, contains two tongues of unstratified core material interbedded in the coarse biocalcarenites which represent lateral extensions of the colonial organisms during short periods of quiescence. Spicules are completely absent and the core-derived fragments are large and abundant.

Sections 7, 8, 9, and 10 are located entirely within the core, with section 10 approximately in the center of the core (fig. 4). No sponge spicules occur in these sections. Pyrite and quartz values decrease progressively toward the center of the core, with some variation in the quartz values due to its presence in pocket fillings. Values of both clasticity and frequency of the organisms reach infinity since distinct, individual fragments are replaced by a rigidly constructed framework of organisms.

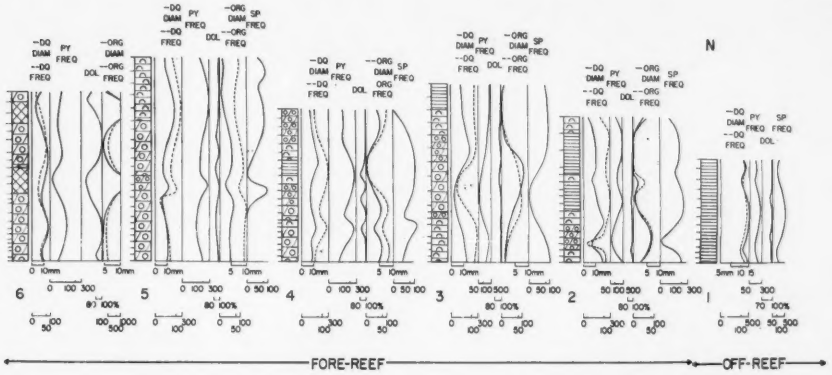

FIG. 3.—Variation of microscopic components in sections 1 to 6.

BATHYMETRIC INTERPRETATION OF MICROFACIES

Reef studies have shown that specific organisms have their maximum development (frequency) at given depths. Likewise, the size (clasticity) of transported clastic mineral and organic components shows an inverse relationship to depth and a direct relationship to agitation. Although specific identification of organisms was difficult due to the high degree of diagenetic dolomitization, these basic facts provided the basis for a relative bathymetric classification of the

MICROFACIES 1	DOLOMITIC SHALE
MICROFACIES 2	DOLOMITIC SHALE WITH SCATTERED ORGANIC FRAGMENTS
MICROFACIES 3	FINE-GRAINED DOLOMITIC BIOCALCARENITE
MICROFACIES 4	COARSE-GRAINED DOLOMITIC BIOCALCARENITE
MICROFACIES 5	MASSIVE DOLOMITIC BIOCONSTRUCTED LIMESTONE
MICROFACIES 5A	BIOCONSTRUCTED DOLOMITIC LIMESTONE WITH POCKETS OF BIOCALCARENITE

LEGEND

D Q DIAM--DETRITAL QUARTZ DIAMETER
D Q FREQ--DETRITAL QUARTZ FREQUENCY
PY FREQ--PYRITE FREQUENCY
DOL--PERCENTAGE DOLOMITE
ORG DIAM--ORGANISM DIAMETER
ORG FREQ--ORGANISM FREQUENCY
SP FREQ--SPICULE FREQUENCY
⊣ POSITION OF THIN SECTION

10'
5'
0'
VERTICAL SCALE

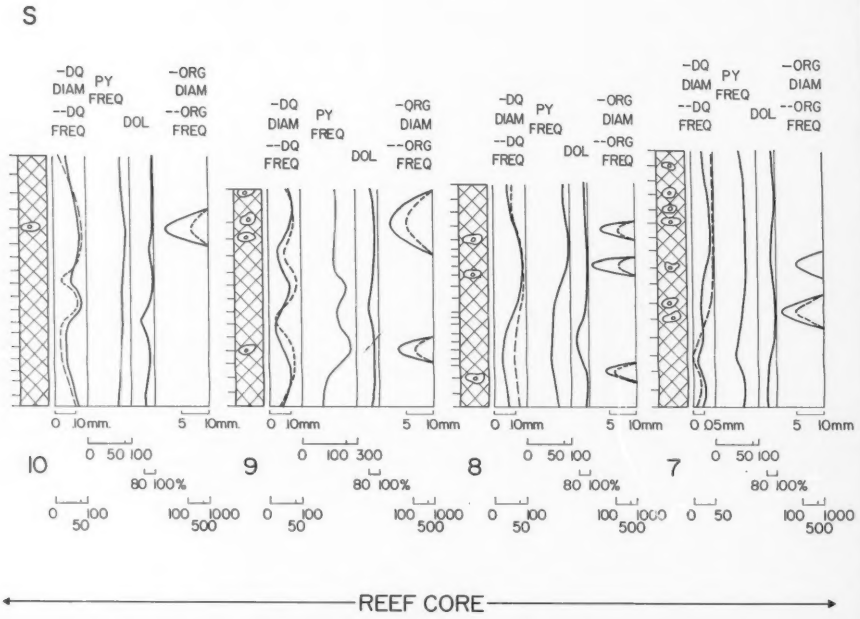

FIG. 4.—Variation of microscopic components in sections 7 to 10.

microfacies. This measure was not a quantitative one determined directly from microscopic examination but was the result of integrating the various quantitative counts and correlating this information to the microfacies.

Microfacies 1 represents material that accumulated under relatively quiet, still-water conditions where depth prohibited waves and currents from agitating the bottom. This is illustrated by the fine-grained components of the shale and the abundance of sponge spicules oriented parallel to bedding. The complete absence of reef-derived organic fragments indicates that the reef structure had little direct effect on the accumulating deposits. This microfacies is typical of the Mississinewa Shale which is the normal inter-reef deposit.

Microfacies 2 is the first to indicate the effects of the reef on normal inter-reef sedimentation. It is a shale, not distinguishable from microfacies 1 without petrographic analysis. Sponge spicules with various orientations are indicative of increased turbulence and agitation. Presence of reef-derived organisms in the form of recrystallized fragments indicates the proximity of a reef structure and the effect of increased transporting power of the water. The decreased abundance of iron sulfide is also indicative of more agitated conditions yielding a high Eh factor relative to the inter-reef surroundings. This microfacies is typical directly adjacent to the dipping bioclastics and to the shale units that extend nearly to the core as thin bands.

Microfacies 3 is the first occurrance of the reef proper as it is approached from the inter-reef shales. Spicules are scarce. The size and frequency of the organic fragments are greatly increased indicating a greater intensity of agitation and competency. The organisms are difficult to identify individually due to dolomitization but they are clearly fragments of the core which became detached by wave action or disintegration and behaved as clastic particles transported off the core to accumulate as thick beds inclined radially away from it. This microfacies is found chiefly at the extremities of the great biocalcarenitic wedges that penetrate into the shales.

Microfacies 4 is characterized by coarse, recrystallized core fragments. Spicules are absent and the clay content is small indicating agitation sufficient for removal of the fine material. This microfacies is related to microfacies 3 and can best be distinguished by microscopic examination, although textural differences can be seen in the outcrop. Both are products of detached core particles that accumulated as thick biocalcarenitic beds. However, because microfacies 4 is located directly adjacent to the core, organic clasticity and frequency show a marked increase over microfacies 3.

Microfacies 5 occurs within the unstratified core. The complete absence of spicules, the low quartz and argillaceous contents except in the pockets, and the fossil fragments being replaced by a solidly constructed network of organisms, indicate shallow conditions with a high intensity of agitation by currents and wave action that stimulated reef growth. Microfacies 5A is not a separate type but a special variety of microfacies 5. It is so designated because the thin sections happened to be cut in a void or cavity in the massive Stromatoporoid framework which became filled with a variety of small organic and inorganic fragments brought by current action.

The relative bathymetrical curves, showing for each investigated section the variation of depth in time, have a scale along which the microfacies are classified according to decreasing relative depth from left to right. These curves allow a comparison of the evolution of local points during the development of the reef structure (fig. 5).

GENERAL CONCLUSIONS

The microfacies which have been described represent a succession that has a vertical as well as a horizontal significance. It is possible to represent the changing conditions during reef growth by an ideal succession corresponding to a shallowing in time and in space which illustrates the history at a single point where the reef established itself on the shales and grew upward into a solid framework, as well as lateral changes encountered when approaching a reef from inter-reef deposits.

With diminished depth and increased agitation (microfacies 1 to microfacies 5, or laterally from the shales to the reef core)

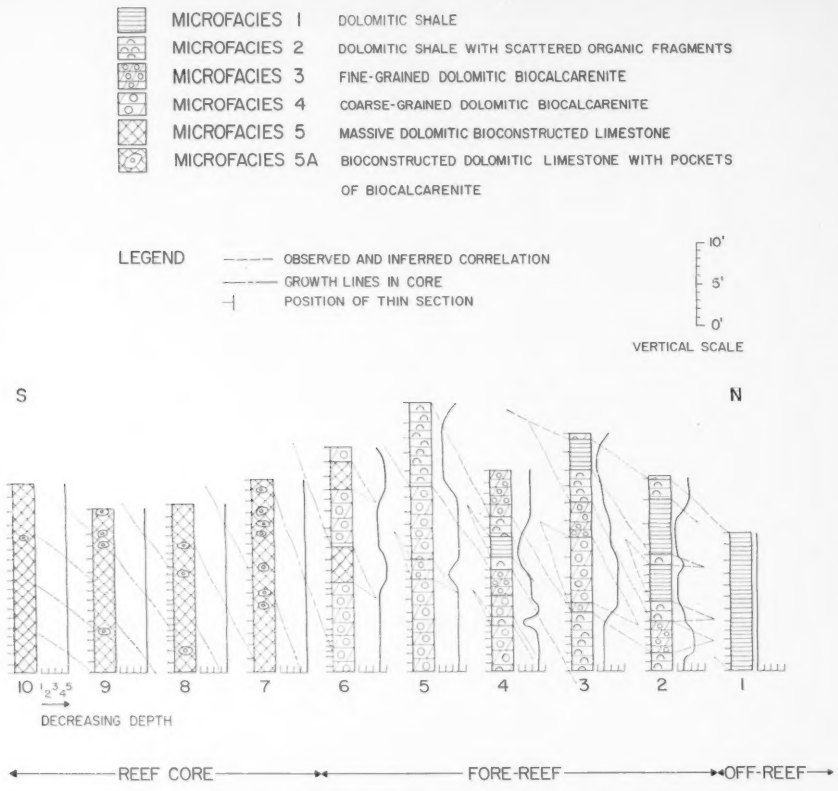

FIG. 5.—Comparison of relative bathymetric curves and microfacies correlations of investigated sections.

the following variations are noted (fig. 6).

1. The index of clasticity of detrital quartz diminishes gradually from a maximum in the shale to a minimum in the core. Strong but local increases may occur at the core of the reef due to fillings of pockets.

2. The frequency of detrital quartz nearly parallels clasticity and has a maximum value in the shale that diminishes toward the core. This parallelism indicates normal supply from the inter-reef area.

3. The frequency of pyrite varies parallel with the quartz and diminishes from a maximum in the shale to a minimum in the core. This parallel variation is expected since the same currents which were responsible for the quartz grains also transported the iron.

4. Dolomitization is very high throughout the fore-reef strata but has a slight general tendency to decrease toward the core, probably due to porosity conditions. No relationship could be found between dolomitization and the other quantitative measures.

5. The index of clasticity of organic fragments increases from zero in the shales to infinity at the constructed core. This curve is directly opposed to quartz and pyrite due to the fact that the organic fragments originated in the reef and were distributed radially outward, whereas pyrite and detrital quartz were distributed by more general currents originating from outside the reef.

6. The frequency of organic fragments parallels its clasticity, increasing from zero in the shale to infinity at the core. As the core is approached, particles simultaneously become larger and more abundant.

7. The frequency of the monoaxonic sponge spicules shows a variation that is parallel to quartz and pyrite. Values are at a maximum in the shale and reach zero at the core. The siliceous sponge spicules belong to the normal fauna of the inter-reef shales. It is important to note that these spicules provide the only clue in the shales for the prediction of the reef. Indeed, away from it (microfacies 1) the spicules are oriented parallel to the bedding. Approaching the reef (microfacies 2, 3 and 4) the spicules display increasingly variable orientations until they disappear.

8. The relative bathymetric curve nearly corresponds to the curves for the clasticity and frequency of the organic fragments since they provide a good index of the intensity of the agitation of the water. It is obvious that in this example the clasticity and frequency of the quartz grains are inversely related to the depth variations.

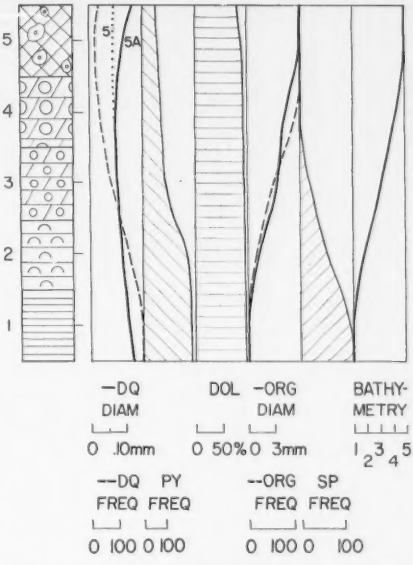

FIG. 6.—Idealized column showing variations of mineral and organic elements with microfacies.

ACKNOWLEDGEMENTS

The writers gratefully acknowledge the friendly co-operation and interest of Dr. Charles Deiss, Head of the Indiana Geological Survey, and Dr. Deiss' collaborators.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 29, NO. 2, PP. 172–177
FIGS. 1–4, JUNE, 1959

THE PETROLOGY OF SOME PENNSYLVANIAN BLACK "SHALES"[1]

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U. S. Army and Iowa State College

ABSTRACT

Black fissile "shales," from some Missourian and Virgilian cyclothems of central Iowa and eastern Nebraska, have been analyzed to determine their chemical and physical properties, the stratigraphic, petrographic, and paleontologic successions over wide geographic areas, and the environment of deposition suggested by these parameters.

The stratigraphic succession commonly consists of three basic elements: a lower black fissile siltstone; a medial black "varved" siltstone; and, an upper gray to gray-green shaly siltstone.

Organic contents range from 2 to 26 percent. Acid-soluble contents range from 11 to 38 percent. An inverse relationship between acid-soluble constituents present, and organic content exists. A direct relationship between organic content, fissility, and radioactivity occurs.

Petrographically, the silts are predominantly quartz, with lesser amounts of illite, kaolinite, vermiculite, pyrite, and carbonates. The siltstones have an average mineral composition within the range of sub-graywacke to graywacke. Sorting coefficients range from 1.9 to 4.3. No general trend in the degree of sorting is apparent.

A definable stratigraphic, petrographic, and paleontologic succession occurs, and can be traced over a wide geographic range. The stratigraphic and paleontologic characteristics, as well as many other features, have their closest association with modern tidal flat deposits. The deposits apparently accumulated in both regressive and transgressive seas. The cyclothem boundary occurs within these black silt intervals.

INTRODUCTION

Much has been written concerning cyclothem deposits within the Pennsylvanian system of the mid-continent region. Most of this literature discusses descriptive stratigraphy, paleontologic analysis, mode of origin of the cyclothems, and petrography of selected members. The petrography of the black "shale" members has been slighted. To the best of our knowledge, nothing concerning the petrography of the black "shale" members of the Pennsylvanian of Iowa has been recorded.

This investigation was pursued with the following questions in mind: (1), what are the chemical and physical properties of the black "shale" members; (2), do definable stratigraphic, petrographic, and paleontologic successions occur within these members, which maintain themselves when traced over a wide geographic and stratigraphic range; (3), what do these successions reveal concerning the environment of deposition?

STRATIGRAPHIC SUCCESSION AND GEOGRAPHIC AREA OF STUDY

Specimens for detailed study were collected from the Oread, Wyandotte, Dennis, and Swope Formations from central and western Iowa, as well as eastern Nebraska. Comparison of stratigraphic succession of two black "shale" members within the Marmaton and Cherokee Groups of Iowa have been made.

Figure 1 illustrates the variation, and similarity of stratigraphic succession within the members at different stratigraphic levels.

Three lithologies characterize the section. Overlying the dense, dark-gray fusulinid-bearing limestone, of the "Levenworth type," there is approximately one foot of hard, black, fissile to blocky siltstone which generally is softer near the top than near the bottom. Conodonts, fish remains, and pectenoids are commonly found in this siltstone.

Overlying the siltstone, the next unit consists of about one foot of hard, black, banded, varve-like siltstone. The most characteristic feature of this unit is the interlayering of discontinuous bands of buff-colored silt. Conodonts are most abundant just above these buff-colored lenses. The fossils generally are found concentrated in small areas, and occur on surfaces with minute desiccation cracks.

The upper most unit consists of one to three feet of gray to olive-colored silt. The silt is noncalcareous and nonfossiliferous at

[1] Manuscript received December 2, 1958.

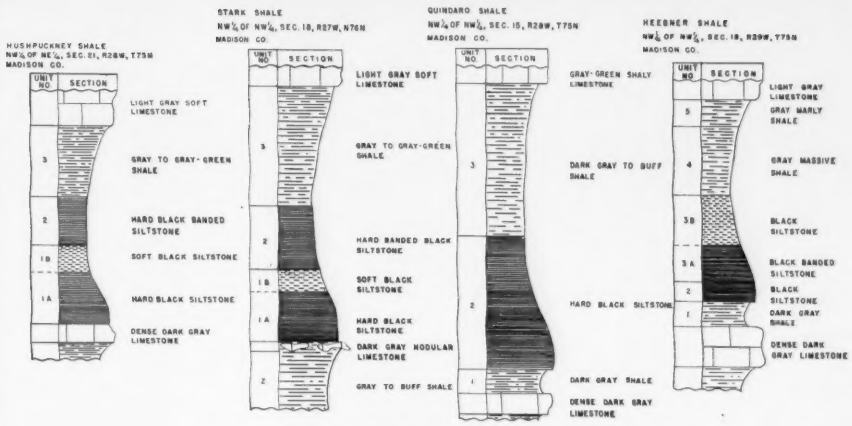

FIG. 1.—Detailed geologic sections.

the base, but becomes progressively calcareous and fossiliferous, until it is nearly coquinoid, near the top.

The pattern of succession, just outlined, is common in the Kansas City Group; whereas, the Heebner (Shawnee) displays a tendency toward an inversion of the lower and middle units. The succession outlined is also in the upper Cherokee and lower Mamaton Groups; however, the black silts of the lower unit overlie coal.

PETROGRAPHY

Organic and Carbonate Content.—The percentages of organic, and acid-soluble constituents are shown in figure 2. Carbonaceous contents range from 1 to 26 percent with the average for total sample being 13 percent. The carbonaceous content of the Hushpuckney and Stark Members decreases upward in the section. The Heebner Member, however, becomes more carbonaceous upward. The quality of the carbonaceous material was not determined.

Acid-soluble contents range from 11 to 38 percent. An inverse relationship between acid-soluble materials present, and organic content is apparent. A direct relationship between organic content, fissility , and radioactive content exists.

Particle Size Distribution.—The cumulative curves (fig. 3), and the size fractions and sorting coefficients (table 1), show a composition of 30 to 40 percent clay, 50 to 60 percent silt, and the remainder, is fine sand. The cumulative curves are relatively straight, the upper units of each member displaying a tendency to become coarse. The coefficients of sorting, according to Trask (1932), vary widely from well sorted (1.9) to poorly sorted (4.3). No general trend in the degree of sorting is apparent.

Mineralogy.—X-ray diffraction patterns, determined for the minus 74 micron fraction of each specimen, and optical petrographic studies reveal a predominance of quartz, with lesser amounts of illite, kaolinite, vermiculite, pyrite, carbonates, and feldspar. The general mineralogical composition is within the ranges of sub-graywacke to graywacke.

One sample was analyzed to determine the distribution of the minerals in different particle size fractions. A small portion of the material was elutriated and the following size fractions isolated: 74-20 microns, 20-12 microns, 10-5 microns, and minus 5 microns. The results of this study are shown graphically in figure 4. Quartz, in the greatest abundance, occurs in the 20-10 micron range, to a lesser extent in the 74-20 and 10-5 micron range, and to an even lesser extent in the minus 5 micron range. Muscovite is most abundant in the 20-10 micron fraction, and occurs in lesser amounts in the other fractions. Feldspar has its greatest concentration in the minus 5 micron fraction. The concentration of feldspars in the

TABLE 1.—*Size fractions and sorting coefficients*

Shale member	Unit	Clay %	Silt %	Sand %	Silt & Sand %	Sorting coefficient
Hushpuckney (Pammel Park) (Madison Co.)	1-A	40	45	15	60	3.74
	1-B	35	53	12	65	3.79
	2	32	50	18	68	4.2
Hushpuckney (Adair Co.)	1	39	47	14	61	4.3
	2	32	60	8	68	2.2
Stark (Adair Co.)	1	43	46	11	57	2.3
	2	30	53	17	70	2.86
Heebner (Madison Co.)	2	38	53	9	62	2.92
	3-A	33	54	13	67	2.78
	3-B	22	58	18	76	2.79
Stark (Pottawattomie Co.)		48	40	12	52	4.2
Heebner (Cass Co.) Nebr.		37	49	14	63	2.87
Quindaro (Madison Co.)	2	41	51	8	59	2.8
Quindaro (Adair Co.)	2	25	60	15	75	1.9

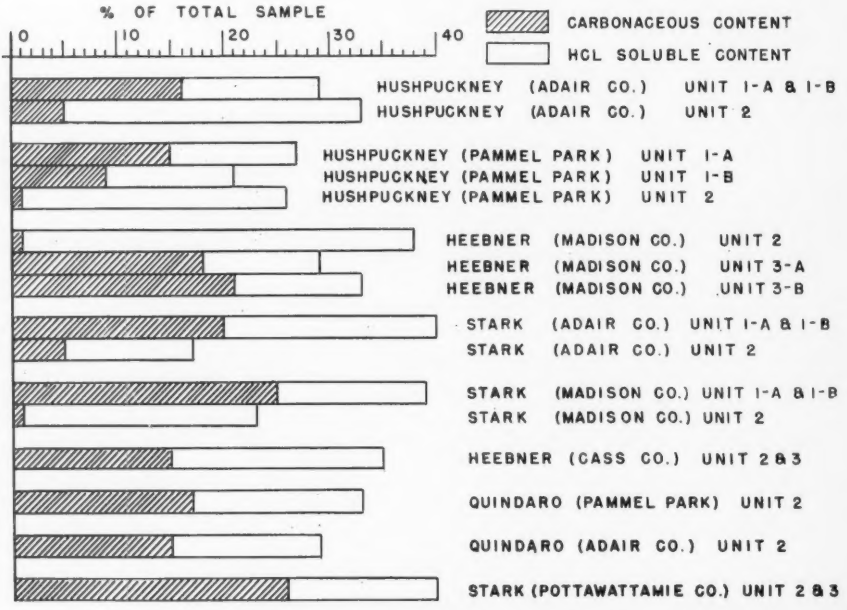
% OF TOTAL SAMPLE
0
10
20
30
40
CARBONACEOUS CONTENT
HCL SOLUBLE CONTENT
HUSHPUCKNEY (ADAIR CO.) UNIT 1-A & 1-B
HUSHPUCKNEY (ADAIR CO.) UNIT 2
HUSHPUCKNEY (PAMMEL PARK) UNIT 1-A
HUSHPUCKNEY (PAMMEL PARK) UNIT 1-B
HUSHPUCKNEY (PAMMEL PARK) UNIT 2
HEEBNER (MADISON CO.) UNIT 2
HEEBNER (MADISON CO.) UNIT 3-A
HEEBNER (MADISON CO.) UNIT 3-B
STARK (ADAIR CO.) UNIT 1-A & 1-B
STARK (ADAIR CO.) UNIT 2
STARK (MADISON CO.) UNIT 1-A & 1-B
STARK (MADISON CO.) UNIT 2
HEEBNER (CASS CO.) UNIT 2 & 3
QUINDARO (PAMMEL PARK) UNIT 2
QUINDARO (ADAIR CO.) UNIT 2
STARK (POTTAWATTAMIE CO.) UNIT 2 & 3

FIG. 2.—Carbonaceous and HCl-soluble contents.

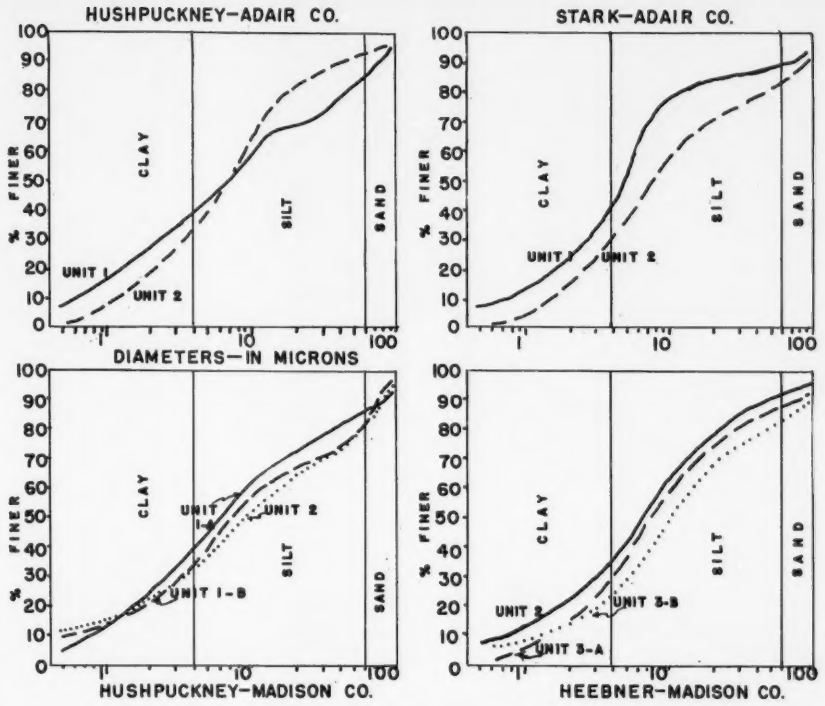

FIG. 3.—Particle size distribution curves at selected stratigraphic intervals.

finest fractions leads one to suspect authigenic development of this mineral. No attempt to resolve this question has been made during this study.

Peaks for the carbonate and the clay minerals, other than illite, were not found. This probably is due to complete destruction of the carbonates, and partial alteration of the clay minerals by the nitric-perchloric acid treatment utilized to remove organic material.

ENVIRONMENT OF DEPOSITION

The black siltstones of southwest Iowa show some similarities to the deposits found in all of the modern environments where black muds are being deposited.

After carefully considering such environments as deep land-locked basins, tidal lagoons, shallow anaerobic sea shelves, and tidal flats, it is concluded that the Pennsylvanian black silts display closest similarities to the Wadden Sea tidal flat deposits.

Comparisons, of the Wadden Sea tidal flat deposits and the Pennsylvanian silts, show the following major differences and similarities. The Wadden Sea deposits are more sandy; generally grade from coarse to fine, upwards; and, have a low (5%) organic content. In textural features, and paleontologic types, the two deposits are very comparable. The similarity is particularly apparent in the banded "varved-like" interval.

The greatest difficulty in visualizing the Pennsylvanian silts as being tidal flat deposits is their thinness, despite their stratigraphic uniformity, over such large areal extent. This problem is usually circumvented by postulating a transgressive sea. Van Straaten (1954 a, b) indicates that the

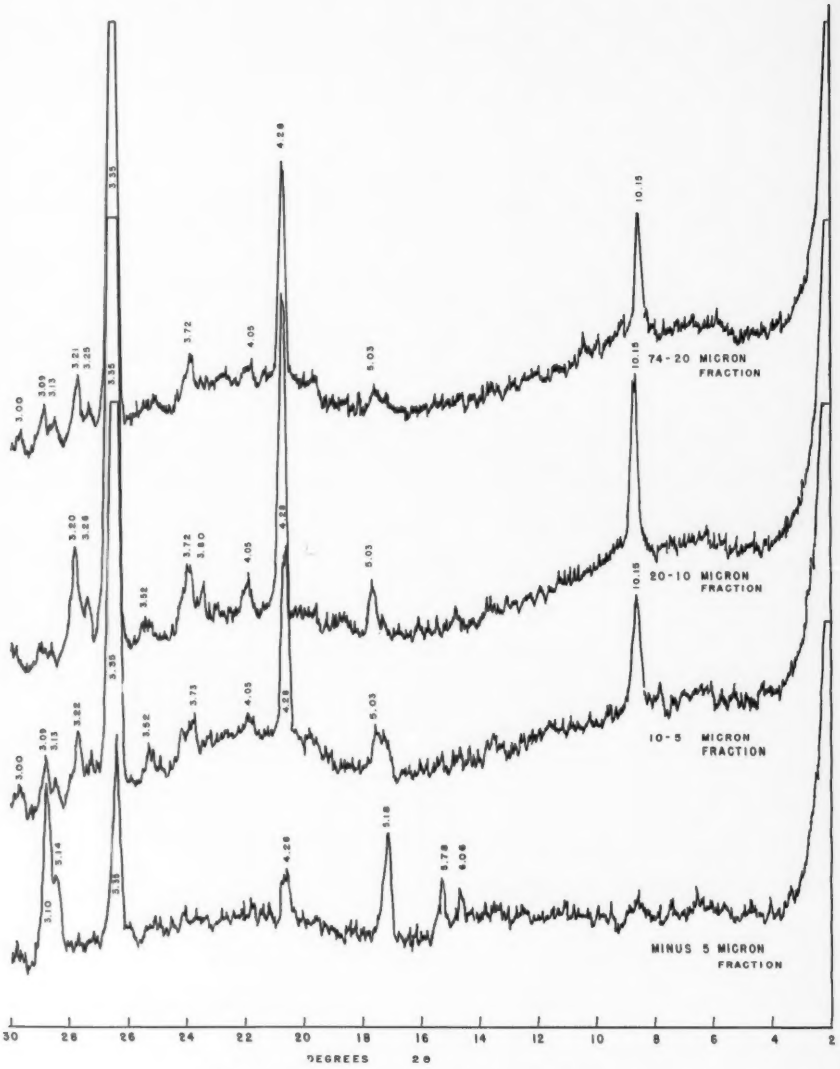
74-20 MICRON FRACTION
20-10 MICRON FRACTION
10-5 MICRON FRACTION
MINUS 5 MICRON FRACTION
DEGREES 2θ
30 28 26 24 22 20 18 16 14 12 10 8 6 4 2

FIG. 4.—X-ray diffraction patterns of Stark Shale.

Wadden Sea is transgressive, and that the upward particle size decrease is a reflection of this transgression.

It has been pointed out that the Pennsylvanian silts coarsen upward in the section. By comparison, does this indicate deposition of the Pennsylvanian silts in a regressing sea? The question necessitates a consideration of the relationships of the black silt to other members of the cyclothem in which it occurs.

The black silt intervals (fig. 1) overlie the dark-gray fusulinid-bearing limestone member in one of two ways: the black siltstone may rest directly upon the limestone without physical evidence of an unconformity; or it may be separated from the limestone by a thin shaly interval in which the brachiopods *Marginifera*, *Derbyia*, and others, occur.

If it be recalled that fusulinids are generally accepted as representing deeper, clear water deposition, then, the lithologic and paleontologic succession, coupled with the tendency of the particle size to coarsen upward, suggests a regressive phase of deposition from the underlying limestone through part of the black siltstone unit.

It is accepted without question that from the base of the upper unit upward, to the overlying massive limestone, that a transgression is signified.

The black silts must represent, therefore, both regressive and transgressive phases of deposition; and, the cyclothem break must occur within some part of either the lower or the middle unit.

CONCLUSIONS

The authors find that definable stratigraphic, petrographic, and paleontologic successions occur within these members, and that these successions are maintained over wide geographic and stratigraphic range.

The "shales" are siltstones, and have an average mineral composition within the range of graywacke to sub-graywacke.

The environment of deposition seems to be most closely allied to tidal flat deposits, the materials having accumulated in both regressive and transgressive seas.

The cyclothem boundary occurs within these black silt intervals.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 29, NO. 2, PP. 178–185
FIGS. 1–2, JUNE, 1959

ESTIMATION OF A MINIMUM DEPTH OF BURIAL FOR A PENNSYLVANIAN UNDERCLAY[1]

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Lafayette, Indiana and Bloomington, Indiana

ABSTRACT

A sample of Upper Block underclay (middle Pennsylvanian) was taken near Brazil, Indiana, and its void ratio was determined in the laboratory. By dispersing, resedimenting, and reconsolidating the underclay in the laboratory, it was possible to estimate the stress cycle required to consolidate the underclay to its present void ratio. The maximum-stress value determined from the estimated stress cycle was translated into a thickness value of overlying, subaqueous sediments. Results of this initial study permit the estimate that the underclay was once buried under at least 4500 feet of subaqueous sediments, and that at least 3700 feet of Pennsylvanian or post-Pennsylvanian sediments have been eroded in this region of the Illinois Basin. The depth-of-burial estimate is considered to be a minimum one because the systematic increase in void ratio (bed thickness) toward the surface of the reconstructed sediment column has not been taken into account.

INTRODUCTION

Reliable estimates of the depths of burial of ancient sediments are of value to geologists. Almost without exception—whether investigating the genesis of coal, the origin of sedimentary-rock structures, the paleogeography of a region, *et cetera*—the geologist is at an advantage in his speculations if he has some knowledge of the depth to which the strata in question were buried. These considerations prompted the authors to attempt to estimate the depth of burial of a Pennsylvanian underclay. The investigation utilized many of the concepts and techniques common to the field of modern soil mechanics.

Quantitative work on the estimation of depth of burial of ancient sediments is sparse. Pioneering work on the quantitative relationships between the degree of compaction of sediments and depths of burial was done by Sorby (1908), Hedberg (1926, 1927, 1936), and Athy (1930). Athy (1930, p. 23) estimated that 1400 to 2500 feet of Permian and younger sediments had been removed by erosion in a region in north-central Oklahoma and that 4000 to 4500 feet of overburden had been removed from above the lower Pennsylvanian strata near Bartlesville, Oklahoma. His estimates were based upon about 2200 density and 200 porosity determinations. Skempton (1944) and Jones (1944) added to, and refined, the quantitative data on the progressive consolidation of muddy sediments with increasing depth of burial. Jones (1944, p. 145) revised Athy's estimate of the thickness of strata removed by erosion by adjusting Athy's value for the density of the clay at the top of the original series. Taylor (1950, p. 701) made an attempt to develop a relationship between sand-grain contacts in Mesozoic sandstones and depths of sandstone burial. Neumann and Jacob (1956) investigated the soil-mechanical properties of European brown coals (Eocene to Miocene) and discussed the problems involved in estimating vanished overburden from their data (p. 316).

In 1956 one of the authors (Harrison), assisted by Mr. H. Y. Loo, attempted a consolidation test (Taylor, 1948, p. 212) of a Pennsylvanian underclay in the soil-mechanics laboratory at Northwestern University. Consolidation test results have been used (Harrison, 1958) in estimating the maximum stresses exerted on clayey silts by Pleistocene ice masses, and it was thought that a similar approach could be used to estimate the greatest previous stresses that ever existed on underclays (where found as

[1] Manuscript received September 10, 1958. Topic presented for discussion by W. Harrison at the Conference on Sedimentary Rock Research at Indiana University on March 2, 1957. Published by permission of the State Geologist, Indiana Department of Conservation, Geological Survey.

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[3] Indiana Geological Survey.

clayey silts). The consolidation-test result of the underclay could not be interpreted, however, as it was impossible to trim the test sample properly for the consolidometer ring (McRae, 1948, fig. 4). G. A. Leonards suggested the laboratory study described herein that was used to estimate the depth of underclay burial.

BACKGROUND STATEMENT

The void ratio[4] of a sediment is the ratio of the volume of voids to the volume of solids and as such can be related to the consolidation[5] of the sediment. The particular amount of consolidation of a sediment may be the result of stresses set up by one or more of the following: the weight of overlying sediments, drying forces, tectonic compressive forces, diagenetic changes, and possibly other factors.

The primary assumption in this work may be stated as follows: *The amount of consolidation of the underclay studied is solely the result of the stress exerted upon the underclay by the greatest previous weight (greatest previous thickness) of overlying sediments (compensated for buoyancy) minus the decrease in stress resulting from unloading of the underclay in response to subsequent erosion of overlying sediments.*

The problem, then, is to estimate the *maximum* stress to which the originally unconsolidated underclay has been subjected. It is realized that the present void ratio is not the minimum void ratio which the underclay has attained because the underclay has been rebounding (or expanding) since commencement of unloading.

THE UNDERCLAY STUDIED

The sample procured for study was obtained from an exposure of Upper Block underclay (middle Pennsylvanian) in the SW¼ sec. 35, T. 14 N., R. 7 W., Brazil West, Indiana, quadrangle. The sample site was in a freshly cut trench where the underclay was approximately 5.5 feet thick. The underclay in the sample zone was typically light gray, dull to glossy (on joints), noncalcareous, gritty, slightly slickensided, and very stiff. A present overburden thickness of some 50 feet was calculated as exerting a stress of approximately 3.7 kg/cm² on the underclay bed.

A cube of underclay about 1 cubic foot in volume was cut from a zone 1 foot to 2 feet below the contact of the underclay with the overlying coal seam. The zone sampled was about 1.5 feet above a zone of concretions, and the underclay itself was some 15 feet below the local water table. (Strip-pit operations required pumping of the area being mined.) As soon as the sample was taken it was coated with Gulf Petrowax A for transport to the laboratory. It was assumed that the sample had not been subjected to drying subsequent to deposition and consolidation.

A prism of the underclay measuring roughly 6 cm×6 cm×6 cm was cut from an unjointed portion of the sample by means of a concrete saw. The prism was immediately weighed in air, coated with paraffin, and weighed again in water. The volume of the prism was calculated and the specific gravity of the mineral grains was determined by the pycnometer method. The void ratio of the underclay was then computed according to the relation

$$e=\frac{VG\gamma_w}{W_s}-1$$

where V is the sample volume, G is the specific gravity of solids (mineral grains), γ_w is the unit weight of water, and W_s is the dry weight of the sample. The void ratio of the sample was found to be 0.236. An average void ratio of roughly 0.26 was estimated for this particular Upper Block underclay. This value (0.26) is deemed a conservative one and was arrived at by a detailed analysis of the laboratory test data, too lengthy to present here.

A size analysis involving sieving and pipette procedures and expressing results in terms of the Wentworth scale showed the

[4] For studies of the consolidation of sediments, *void ratio* is a more convenient quantity than porosity "since the void ratio is a variable given in terms of a constant (the volume of solids), whereas the porosity is a variable given in terms of another variable, the total volume" (Terzaghi, 1940, p. 80).

[5] "Consolidation" corresponds most closely to "compaction" in geological nomenclature. "Consolidation" is "the gradual process which involves, simultaneously, a slow escape of water and a gradual compression, and which also involves a gradual pressure adjustment" (Taylor, 1948, p. 212).

underclay to be composed of 5.2 percent sand, 53.7 percent silt, and 41.1 percent clay by weight (Murray, 1957, table 3, sample 7). The pH value for a suspension of the underclay is estimated at about 7.8 (table 4, sample 7). Clay-mineral determinations of the less-than-2-micron oriented fraction were made by J. L. Harrison, mineralogist of the Indiana Geological Survey. X-ray diffraction analysis revealed kaolinite, illite, and mixed-layer minerals (respective ratios being approximately 3:1:1). No significant amounts of montmorillonite or halloysite were found; these minerals may give a sediment unusual properties (Grim, 1949). It is probable that little diagenesis has occurred in the Upper Block underclays since their deposition (H. H. Murray, 1956, oral communication). Shultz (1958, p. 391) has pointed out that "underclay materials are essentially as they were [when] transported into the basin."

The following Atterberg limits (Taylor, 1948, p. 27) were determined for the sample studied: liquid limit, 40; plastic limit, 22. The fact that the liquid limit did not change during the long-time laboratory test indicates a lack of sample "weathering" during the test (Bjerrum and Rosenqvist, 1957, p. 7).

SAMPLE DISPERSAL AND RESEDIMENTATION

Inasmuch as it was not feasible to estimate the maximum prestress (preconsolidation load) of the underclay directly by means of a standard laboratory consolidation test (p. 181), the following general approach was taken. The underclay was dispersed, resedimented, and gradually reconsolidated. Laboratory resedimentation by the techniques used has been found to reproduce the natural sediment structure closely (Skempton, 1944, p. 134; Raju, 1956, p. 17; Bjerrum and Rosenqvist, 1957, p. 12).

Sample dispersal was carried out by means of distilled water and a motor-driven mixer (stirred for 30 minutes). A number of attempts were made to secure a homogeneous artificial sediment by direct flocculation. When flocculation was attempted, however, the sand-sized particles would drop rapidly out of suspension and form a coarse layer at the base of the artificial underclay sample. To avoid this sorting effect it was decided to develop the sediment by a slurry technique.

A portion of the underclay was dispersed by means of a mortar and rubber-tipped pestle until all of it passed a No. 80 U. S. Standard sieve. This material then was transformed into a slurry using distilled water. The desirable slurry consistency had to be determined by trial and error, and the best slurry was one which formed relatively small droplets when poured from an evaporating dish into a column of distilled water (fig. 1, lucite tube). The slurry droplets fell through approximately 45 cm of water and formed a homogeneous slurry on the bottom of the tube. The small percentage of material which became dissociated in the falling process was flocculated by the addition of 5 drops of 0.5N HCl to the distilled water in the tube. The HCl was added after about one-half of the sediment had been established.

LABORATORY CONSOLIDATION

The laboratory consolidation techniques followed in this study imply one-dimensional consolidation (which is probably the case in deeply buried strata). By closely simulating natural consolidation (secondary consolidation[6] excepted), it is possible to investigate the pressure-void ratio relationships which are characteristic of the underclay studied. Initial laboratory consolidation was carried out in a specially designed sedimentation-compression device (fig. 1). Standard laboratory consolidation techniques were used to achieve pressures beyond the capacity of the sedimentation-compression device.

An initial consistency was given the resedimented underclay sample by allowing water to flow through the sediment voids and lower porous disk (fig. 1) and out the tap at the base of the tube. An hydraulic gradient (Taylor, 1948, p. 97) of approximately four was employed. One can see in the diagram that there is a balanced system consisting of a piston on one side and a suspended oil tank on the other. Weights are added on the piston side to balance the weight of oil which is placed in the tank. The

[6] Secondary consolidation involves a reduction in water content at essentially constant intergranular pressure.

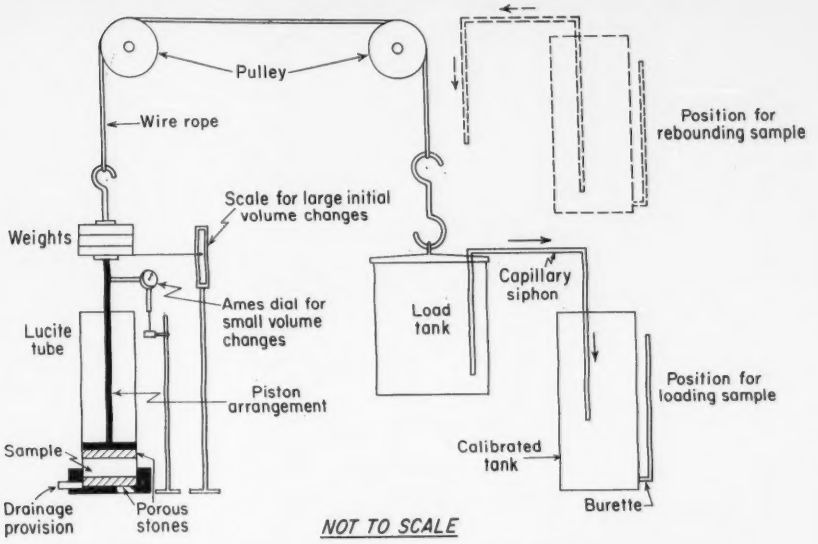

FIG. 1.—Schematic diagram of apparatus used for initial laboratory consolidation.

piston then is applied to the sample surface in the tube, and oil is siphoned from the suspended tank by use of a capillary siphon. The unbalance thus placed into the system represents the load placed on the sediment; this load is equal to approximately 0.02 kg/cm²/day. Under this slowly increasing pressure the sample consolidates and reduces in volume along a so-called "sedimentation-compression" curve. The curve obtained is characteristic of the sediment studied (dependent upon its grain-size distribution, grain mineralogy, grain shapes, *et cetera*). The volume-change data for the curve are obtained from the dial and scale shown in figure 1. The oil siphoned from the loading tank is directed into a calibrated second tank so that weights of oil can be determined directly.

In nature, the slow process of sedimentary loading may be interrupted by unloading caused by erosion. This unloading causes sample rebound. Rebound was simulated in the laboratory by raising the calibrated tank above the level of the loading tank and allowing oil to siphon back into the loading tank to reduce the unbalance existing in the system. Siphoning in the rebound case was again at such a rate as to decrease pressure on the sample by approximately 0.02 kg/cm²/day. The results of the simulated natural loading and rebound are presented in table 1 and also on the plot of figure 2.

At the completion of rebound, the sample was placed in the standard laboratory consolidometer, and a typical consolidation test was performed (Lambe, 1951, p. 74). Two cycles of loading and rebound were performed before the capacity of the apparatus was reached. These results can also be found in table 1 and figure 2.

RESULTS OF LABORATORY CONSOLIDATION

The curves presented in figure 2 represent the significant and composite volume-change vs. applied-pressure data for the sample. The value of the compression index, C_c (slope of the void-ratio vs. log-pressure curve), for each curve follows:

1) Sedimentation-compression (end of cycle)	0.32
2) First standard-test loading cycle	0.29
3) Second standard-test reloading cycle	0.25

The data show that all three curves ap-

TABLE 1.—*Summary of data*

Date	Pressure (kg/cm²)	Void ratio	Remarks
Nov. 17, 1957	0.045	1.96	
Nov. 18	0.051	1.85	
Nov. 20	0.064	1.65	
Nov. 22	0.076	1.51	
Nov. 24	0.089	1.42	
Nov. 26	0.103	1.37	
Nov. 29	0.172	1.16	
Dec. 1	0.226	1.11	
Dec. 3	0.276	1.05	
Dec. 7	0.346	0.995	Stopped load; started rebound
Dec. 12	0.268	0.998	
Dec. 16	0.172	1.004	
Dec. 19	0.080	1.008	Stopped rebound; began standard laboratory consolidation test
Dec. 19	0.079	0.983[1]	
Dec. 20	0.158	0.958	
Dec. 21	0.316	0.932	
Dec. 22	0.632	0.864	
Dec. 23	1.264	0.779	
Dec. 24	2.528	0.692	
Dec. 25	5.056	0.604	Stopped load; began rebound
Dec. 26	1.264	0.622	
Dec. 27	0.632	0.645	
Dec. 28	0.316	0.671	
Dec. 29	0.158	0.701	
Dec. 30	0.079	0.745	Stopped rebound; began reload
Dec. 31	0.158	0.739	
Jan. 1, 1958	0.316	0.717	
Jan. 2	0.632	0.687	
Jan. 3	1.264	0.655	
Jan. 4	2.528	0.617	
Jan. 5	5.056	0.568	
Jan. 6	10.112	0.500	
Jan. 7	20.224	0.423	Stopped load; began rebound
Jan. 8	10.112	0.425	
Jan. 9	5.056	0.442	
Jan. 10	2.528	0.462	
Jan. 11	1.264	0.488	
Jan. 12	0.632	0.514	
Jan. 13	0.316	0.544	
Jan. 14	0.158	0.578	
Jan. 15	0.079	0.631	Stopped test

[1] The initial void ratio for the standard consolidation test is less than the final void ratio of the "sedimentation-compression" process. This indicates that the disturbance incurred during transfer into the consolidometer has had a slight effect on sample volume.

proach each other and tend to form one curve which is very probably curvilinear. This forms the basis for the technique used in predicting the maximum natural consolidation pressure. By knowing the void-ratio *vs.* log-pressure relationship over a range of moderate pressures, it is possible to extrapolate the curve to pressures much beyond laboratory capacity. Knowing the magnitude of the present overburden pressure and estimating an in-place rebound relationship (that due to erosion), it is possible to estimate the maximum consolidation pressure. This pressure is then assumed to be due solely to the weight of overlying sediments.

Conversion of the *weight* of overlying sediments into *thickness* of overlying sediments can then be made. The thickness estimate given in this study does not take into account the systematic increase in void ratio toward the surface of the sediment

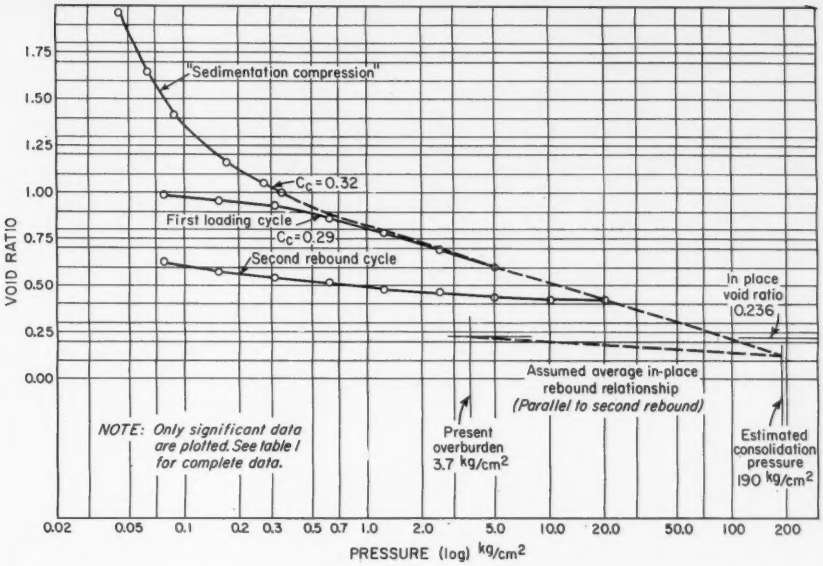

FIG. 2.—Void ratio vs. pressure in laboratory consolidation.

column and, therefore, probably results in underestimating the bed thickness.

The void ratio of the natural underclay sample (assumed to be an undisturbed sample) was 0.236 (p. 179). The curve of the sedimentation test was extended, and an estimated rebound curve was plotted from the present overburden pressure of 3.7 kg/cm² at a slope parallel to the second rebound curve of the standard consolidation test. These extrapolated curves meet at a value of 190 kg/cm²; this value represents the best estimate of the preconsolidation pressure[7] of the underclay. The linear nature of these extrapolations is believed realistic by way of comparison with similar curves in this range of pressure (Skempton, 1953, fig. 11).

EVALUATION OF TECHNIQUES

The sedimentation operation is a crude laboratory attempt to create a sediment which will have a structure similar to a natural sediment. Flocculation may be a more realistic technique for marine deposits. However, for fresh-water sediments, the described procedure appears reasonable. Because the natural sedimentation process is only imperfectly understood (Shultz, 1958, p. 392), the laboratory sedimentation process cannot be fully evaluated. It is well to note in passing, however, that the underclay studied is a very stiff clay and, as Skempton (1944, p. 134) pointed out, " . . . in some stiff clays the grains have become so tightly packed that the natural inter-granular structure does not differ materially from that produced by consolidating the clay from a slurry." It is presumed that the method of forming the artificial underclay sufficiently simulates the natural process so that extrapolation from laboratory data to the natural situation may be made.

The results of Bjerrum, Rosenqvist, and Raju, which were obtained independently, indicate that the slow laboratory-loading process provides a reliable simulation of natural loading during continuous sedimentation. It must be realized, however, that secondary consolidation has in no way

[7] The *preconsolidation pressure* is the maximum pressure at which a sediment has been consolidated at any time in its history.

been considered and is the factor missing from a true simulation of the process in the laboratory.

DEPTH OF BURIAL OF UNDERCLAY

For depths of burial amounting to about 5000 feet the effective overburden pressure is equal to the weight of the overlying material reduced by hydrostatic uplift (Skempton, 1953, p. 52). "Thus, if $\bar{e}$ is the average void ratio in the sediment in a depth z below the surface the effective overburden pressure at this depth is

$$p=\frac{(S_g-1)}{1+\bar{e}}\gamma_w z$$

where S_g is the specific gravity of the grains and γ_w is the density of water. This equation holds good, within close limits, to a depth of the order of 3000 feet or 5000 feet" (Skempton, 1953, p. 53).

For substitution in the above equation a density value for water of 1.01 g/cm³ seems reasonable. The assumed average void ratio ($\bar{e}$) of the underclay has already been estimated as approximately 0.26, and the effective overburden pressure (p) as 190 kg/cm².[8] After examination of the Pennsylvanian column in Indiana and estimation of the relative percentages of sand, silt, and clay grains, a value of 2.72 was estimated for S_g. Substituting into the above equation and solving for z result in a figure of 1365 meters, or approximately 4500 feet, for the thickness of pre-existing sediments. It is emphasized again that this depth-of-burial figure may be somewhat less than the maximum thickness of sediments which may have overlain the underclay (p. 182).

An estimated 800 feet of existing Pennsylvanian sediments occur above this underclay in the Illinois Basin. After this figure is subtracted from the previously estimated 4500 feet, it appears that a minimum of 3700 feet of Pennsylvanian or post-Pennsylvanian strata have been eroded in this region.

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[8] The following observation seems significant. A point determined by the effective-overburden-pressure value (190 kg/cm²) and the average void-ratio value (0.26) for this underclay falls on the curvilinear "void-ratio vs. effective-overburden-pressure" plot for a sample of a clayey silt from Detroit with a similar liquid limit which was subjected to very high laboratory pressures (Skempton, 1953, fig. 11). This is a measure of the reliability of the result obtained here.

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FIGS. 1–5, JUNE, 1959

CHARACTER AND GENESIS OF MASSIVE OPAL IN KIMBALL MEMBER, OGALLALA FORMATION, SCOTT COUNTY, KANSAS[1]

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ABSTRACT

Chemical analyses, weight-loss studies, differential thermal analyses, and X-ray diffraction studies show that massive opal in the Kimball Member of the Ogallala Formation, like opal described by Flörke, is composed of hydrated low-cristobalite that is disordered by differing amounts of low-tridymite, which forms an integral part of the opal structure. The development of tridymite structure in the opal, as proposed by Flörke, is due to incorporation of cations (e.g., Na^{+}, K^{+}, Ca^{+2}, and Al^{+3} among others) into the low-cristobalite structure. It is proposed that the Kimball Member, which is everywhere rich in feldspar and quartz, was leached during formation of the overlying pisolitic caliche, freeing SiO_2 and metal cations which were redeposited as opal having a disordered low-cristobalite structure. Difference in hardness of opal samples is seemingly inversely related to difference in water content; the more hydrated samples have lesser hardness.

INTRODUCTION

Hard, massive opal has been known in the Kimball Member of the Ogallala Formation of western Kansas for many years (Frye and Swineford, 1946). In the summer of 1956, the writers' attention was called to what was thought to be a unique occurrence of soft opal in the Ogallala Formation in Scott County, Kansas. More recent examination of opaline outcrops of the Kimball Member of the Ogallala Formation indicates more widespread occurrence of soft opal than was previously recognized. Studies were undertaken to determine the mineralogic composition of Kimball opal, differences other than hardness between hard and soft opal, and the geologic significance of soft opal in the Ogallala Formation.

OCCURRENCE AND DISTRIBUTION

The soft opal outcrop is located on the Roy Tucker property in the NE¼ NW¼ sec. 5, T. 16 S., R. 34 W., Scott County, Kansas. The opal was collected during brief visits to the locality on August 24, 1956, and on September 7, 1957.

Stratigraphically, the opal occurs as irregular masses in a "mortar bed" (silt and sand grains partly indurated by fine-grained calcium carbonate) in the Kimball Member of the Ogallala Formation near the northern limit of Ogallala outcrops on the south side of Smoky Hill River valley. Rock of this lithology commonly occurs in the Kimball Member 10 or 15 feet below the stratigraphic top of the Ogallala Formation, which is marked by a caliche or pisolitic limestone (Frye, Leonard, and Swineford, 1956, p. 20).

The bed containing the soft opal is 2.5 to 3.0 feet thick, approximately 25 feet below the land surface of the hill tops, and 19 feet below the top of the Ogallala Formation, which is overlain by loess (fig. 1). The massive silicified part ranges from 1.0 to 1.5 feet in thickness and is closely jointed. The soft opal is restricted to the central portions of opaline joint blocks. The most massive opal seems to be restricted to those areas where the containing "mortar bed" is thinnest. Numerous relict grains of quartz and feldspar are disseminated in the opal, which seemingly has developed at the expense of the "mortar bed" host rock.

Reconnaissance of additional opaline outcrops has shown that soft opal is actually widespread and that it occurs in essentially the same geologic setting throughout most of the massive opal exposures.

METHOD OF WORK

The opal was wrapped in water-soaked cotton and placed in an air-tight container as soon as it was collected. In the laboratory, the soft opal was separated from the surrounding hard opal by hand picking.

[1] Publication authorized by the Director, State Geological Survey of Kansas. Manuscript received October 6, 1958.

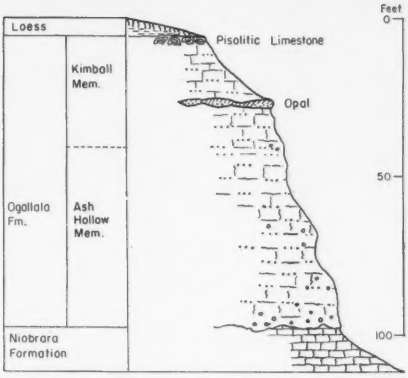

FIG. 1.—Pictorial measured section of Ogallala outcrop in NE¼ NW¼ sec. 5, T. 16 S., R. 34 W., Scott County, Kansas.

Some was immediately placed in water and some was allowed to dry at room temperature.

Studies of optical and physical properties were made on composite samples of the hard opal, of the newly collected soft opal, and of soft opal that had been dried in air. Chemical and spectrographic analyses, weight-loss studies, and differential thermal analyses were made on hard and soft opal. X-ray diffractograms were made of both the hard and soft opal soon after collection. Additional diffraction patterns were made after the soft opal had been allowed to dry in air for 5 months and after both hard and soft opal samples had been heated.

In preparation for the various studies outlined above, impurities (scattered detrital grains of quartz and feldspar) were removed from the opal by hand picking, so that the samples were as nearly homogeneous as possible.

PHYSICAL AND OPTICAL PROPERTIES

Color of the opal ranges from light brownish gray (Munsell 10 YR 6.5/2 and 2.5 Y 6/2) to light gray (N 8.0/2), but the opal locally includes black dendrites. Luster is vitreous to waxy. The opal has conchoidal fracture and generally is massive or structureless. The light-brownish-gray parts, however, are locally granular. Hardness ranges from 4.5 to 6.0, the softer material commonly being restricted to the central vitreous or waxy parts of opaline joint blocks. Hardness of the opal cited by Dana-Ford (1932, p. 475) ranges from 5.5 to 6.5; that cited by Hurlbut (1952, p. 326) ranges from 5 to 6. Both the hard and the soft opal are extremely brittle. On the surfaces of fresh fractures the hard opal was dry, whereas the soft opal seemed to be moist.

Microscopically, fragments of the opal commonly have a stippled appearance in transmitted light; but some of the opal appears colloform and has no stippling. Indices of refraction range from 1.440 to 1.450 in soft material that had not been allowed to dry. The predominant index value of the soft opal approximated 1.446. Indices of both the air-dried soft opal and the hard opal that surrounds the soft opal range from 1.434 to 1.450 but do not commonly exceed 1.440. Indices of refraction for opal cited by Rogers and Kerr (1942, p. 189) range from 1.40 to 1.46.

Between crossed nicols, the soft opal is almost completely isotropic; but the hard opal contains abundant, diversely oriented stringers of weakly birefringent material penetrating the isotropic opal. Both types of opal contain sparse minute inclusions of a strongly birefringent mineral that probably is calcite.

CHEMICAL AND SPECTROGRAPHIC ANALYSES

Tables 1, 2, and 3 show the results of chemical and spectrographic analyses of composite samples of the hard and the soft opal. To nullify the presence of contained water, the chemical analyses have been recalculated so that the weight percents given are those after ignition at 1000°C. Heating the opal samples to 1505°C did not change the chemical analyses significantly except to eliminate sulfur trioxide.

The analyses indicate that the hard opal contains greater amounts of metal cations than does the soft opal. Table 2, in which the relative numbers of atoms are given, demonstrates further that the hard opal contains many more cations than does the soft opal.

WEIGHT-LOSS STUDIES

Loss of weight of samples of both hard and soft opal was determined after drying at room temperature and after heating at various temperatures in order to obtain a

TABLE 1.—*Chemical analyses*[1] *of two composite samples of hard and soft opal from the Roy Tucker property, sec. 5, T. 16 S., R. 34 W., Scott County, Kansas*

	Hard Opal %	Soft Opal %
Silicon Dioxide (SiO_2)	98.27	99.10
Alumina (Al_2O_3) (and MnO_2 and Ga_2O_3 if present)	0.65	0.19
Iron Oxide (Fe_2O_3)	0.10	0.06
Titanium Oxide (TiO_2)	0.00	0.06
Calcium Oxide (CaO)	0.13	0.10
Magnesium Oxide (MgO)	0.68	0.64
Potassium Oxide (K_2O)	0.12	0.06
Sodium Oxide (Na_2O)	0.06	0.02
Sulfur Trioxide (SO_3)	TR	TR
	100.01	100.23

[1] The analyses have been recalculated to weight percents after ignition at 1000°C to nullify the presence of water. TR equals trace.

measure of water content. The soft opal was ground while wet, dehydrated in a desiccator until surface water was evaporated, and then was allowed to dry in air along with dry-ground hard opal for a period of 53 days until the weights of both samples fluctuated daily, seemingly in response to variations in humidity. The total changes in weight on drying at room temperature are shown graphically in figure 2.

After the approximate equilibrium weight at room temperature was reached, the samples were heated in an electric furnace as follows: 105°C for 8 hours, 300°C for 1 hour, and 900°C for 1 hour. Changes in weight of the opal samples on heating are shown in figure 2 and in table 4.

TABLE 2.—*Relative numbers of atoms (cations and oxygen) in hard and soft opal calculated to cristobalite unit cell containing 16 oxygen atoms*

	Hard Opal	Soft Opal
Silicon	7.895	7.935
Aluminum	0.060	0.018
Iron	0.006	0.003
Titanium	0.000	0.004
Calcium	0.011	0.008
Magnesium	0.082	0.077
Potassium	0.013	0.006
Sodium	0.008	0.002
Oxygen	16.000	16.000

TABLE 3.—*Spectrographic analyses of samples of hard and soft opal from the Roy Tucker property, sec. 5, T. 16 S., R. 34 W., Scott County Kansas*

Element	Wave Length	Hard Opal	Soft Opal
Boron	2497.7	0.0x	0.0x
Magnesium	2852.3	x	0.x
Silicon	2881.5	xx	xx
Vanadium	3185.3	0.0x	0.0x
Titanium	3349.1	0.0x	0.0x
Titanium	3361.2	0.0x	0.0x
Titanium	3372.8	0.0x	0.0x
Scandium	3911.8	—	0.0x?
Calcium	3933.6	0.x–x	0.x
Aluminum	3961.5	0.x	0.x
Manganese	4030.7	0.x	0.0x
Iron	3020.5	0.x	0.x–0.0x

0.0x stands for less than 0.1 percent; 0.x, 0.1 to 1 percent; x, 1 to 10 percent; and xx, 10 percent or more. Graphite electrodes and lithium buffer were used. Scandium reported may be from electrode contamination.

At room temperature, as shown in figure 2, after the surface water evaporated the soft opal lost weight more slowly at first than did the hard opal; but as drying progressed, the weight lost by the soft opal slowly increased and nearly equaled that lost by the hard when approximate equilibrium was reached. Toward the end of the drying cycle the soft opal gained and lost weight seemingly in response to fluctuations in humidity, as the hard opal had done within two weeks of the start of drying.

On heating, further loss of weight was shown by both the hard and the soft opal

TABLE 4.—*Cumulative weight percentages lost on heating two composite samples of hard and one composite sample of soft opal*

$$\left(\frac{W_0 - W_n}{W_0} \cdot 100\right)$$

Temperature	Total Weight-Percent Lost		
	Hard	Hard	Soft
Room temperature (approximate equilibrium)	2.027	2.163	1.938
105°C for 8 hours	3.628	3.574	3.155
300°C for 1 hour	5.284	5.144	5.273
900°C for 1 hour	6.467	6.577	8.464

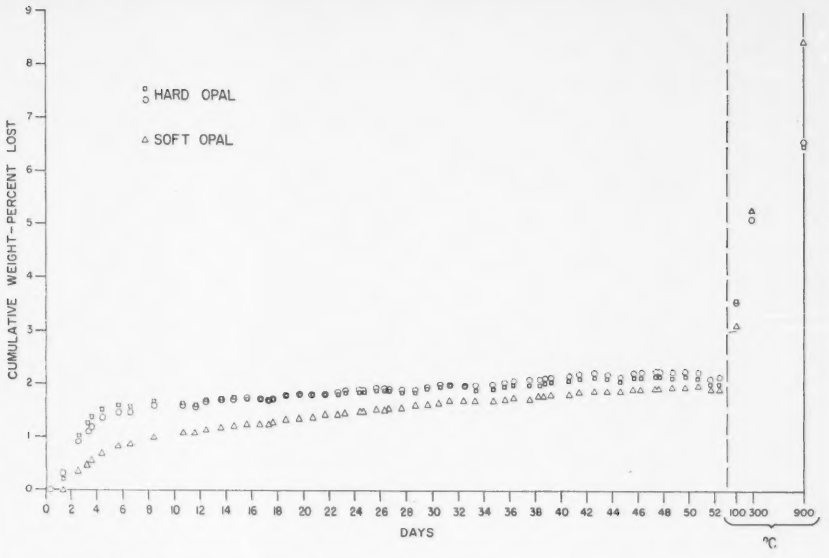

FIG. 2.—Graph showing cumulative percent of weight lost

$$\left(\frac{W_0 - W_n}{W_0} \cdot 100\right)$$

on successive days of drying at room temperature and on heating at 105°C for 8 hours, at 300°C for 1 hour, and 900°C for 1 hour.

(fig. 2 and table 4). On heating for 1 hour at 300°C both hard and soft opal samples showed essentially the same weight loss. Further heating to 900°C brought the total weight lost by the soft opal to about 8.5 percent, whereas the hard opal lost only about 6.5 percent.

DIFFERENTIAL THERMAL ANALYSES

Differential thermal analysis curves for samples of hard and soft opal are shown in figure 3. The two curves have many similarities; nonetheless, distinct differences are to be observed. The sharp endothermic peak at or about 95°C on both curves is attributed to loss of water used in packing the samples. The next endothermic reaction at 170°C in the hard opal and 200°C in the soft opal is similar to that obtained by Flörke (1955b) from what he regarded as disordered low-cristobalite.

Additional endothermic reactions at essentially the same temperatures for both hard and soft opal can be observed on the differential thermal analysis curves. The endothermic reaction superimposed on the exothermic swing at or about 930°C in the curve for hard opal is not present in the curve for soft opal although the exothermic swing is present.

The differences in amplitude of the two curves may reflect both differences in the rate of loss of water at elevated temperatures and differences in heat conductivity due to differences in the amount of contained cations. The differential thermal curve of the soft opal is displaced more in the endothermic direction than is the curve of the hard opal. If, as the weight-loss studies indicate, the soft opal loses water at a greater rate than the hard opal on heating, the soft opal curve should be displaced in the endothermic direction. And, if the greater amount of cations in hard opal in-

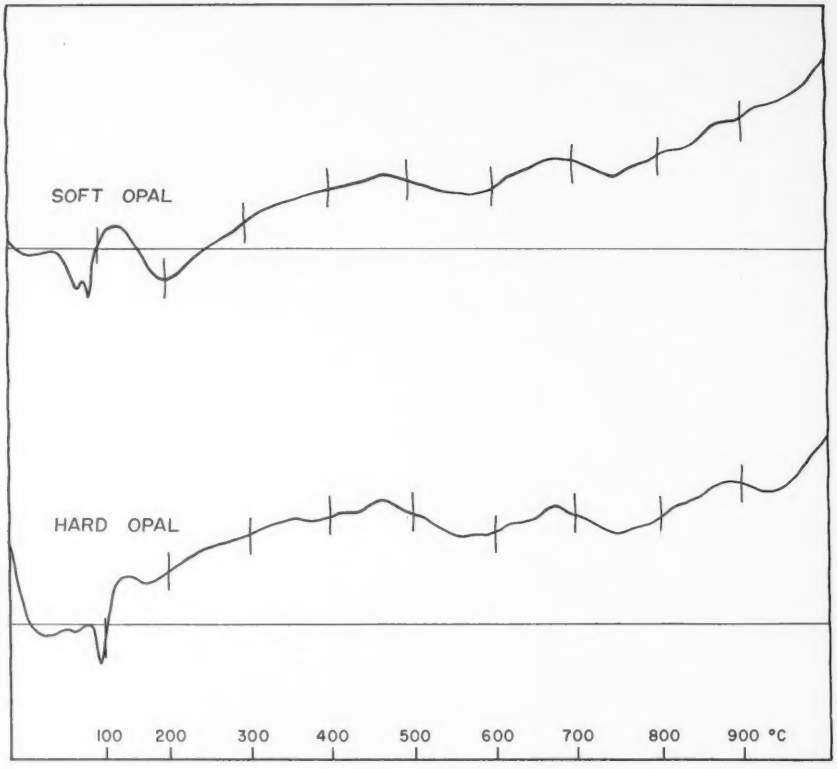

FIG. 3.—Differential thermal analysis curves of samples of hard and soft opal.

creases its thermal conductivity, its curve should be displaced in the exothermic direction.

X-RAY DIFFRACTION DATA

Diffractograms of opal samples were made with a General Electric XRD-3 diffractometer using Cu Kα radiation. The scanning rate was 0.2° 2θ per minute. Samples were crushed in a mortar to pass a 74-micron sieve and packed in plastic sample holders. To inhibit drying, one sample of soft opal was ground in water and wet-sieved through a 125-micron screen.

The diffractogram of the wet-ground sample of soft opal was started at 19° 2θ so that the critical peaks between 20 and 36° 2θ could be recorded before the sample had opportunity to dry. All other patterns were started at 5° 2θ. For comparative purposes, diffractograms were made for the soft opal and the hard opal surrounding the soft core as well as for other opaline samples from various parts of the Ogallala Formation. The d-values of x-ray reflections for the various opal samples are shown in table 5. X-ray studies of both hard and soft opal were made on samples that were heated to 105°, 300°, 900°, and 1500°C in an uncovered crucible and of a sample of soft opal that was allowed to dry in air for 5 months. Diffractograms of these samples are reproduced in figures 4 and 5.

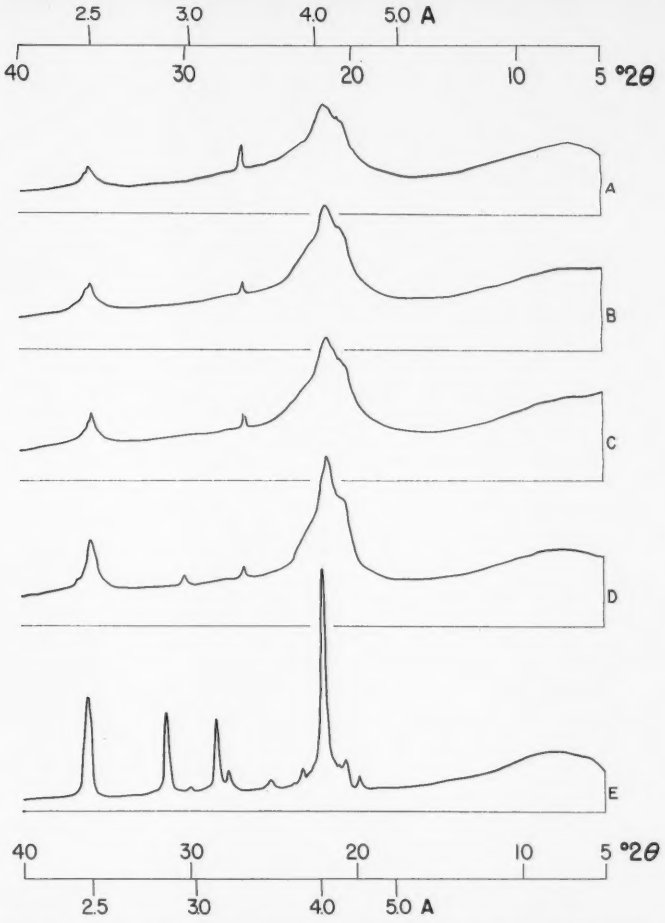

FIG. 4.—Diffractograms of hard opal sample: A) unheated, B) dried at 105°C for 8 hours, C) heated to 300°C, D) heated at 900°C for 1 hour, E) heated at 1505 ± 5°C for 5 hours.

The diffractograms obtained from the unheated samples of hard and soft opal generally are similar (figs. 4 and 5). Both have broad peaks extending from about 4.8 to 3.7A (18.4–24.0° 2θ). Apparent in the broad peaks are reflections at 4.31 and 4.11A (20.6 and 21.6° 2θ); also present in the broad peak in the hard opal trace is a reflection at 4.27A (20.8° 2θ). Both patterns show peaks at 3.35 and 2.51A (26.6 and 35.7° 2θ); the 2.51A peak in the hard opal trace has a shoulder at 2.47A (36.3° 2θ). The hard opal pattern also has a broad, indistinct reflection between 10 and 18A that appears as a broad swell.

The reflections at 4.27 and 3.35A are attributed to quartz. The broad swell, the broad peaks, and the lesser peaks are characteristic of patterns of other opal samples studied (table 1) and patterns shown by

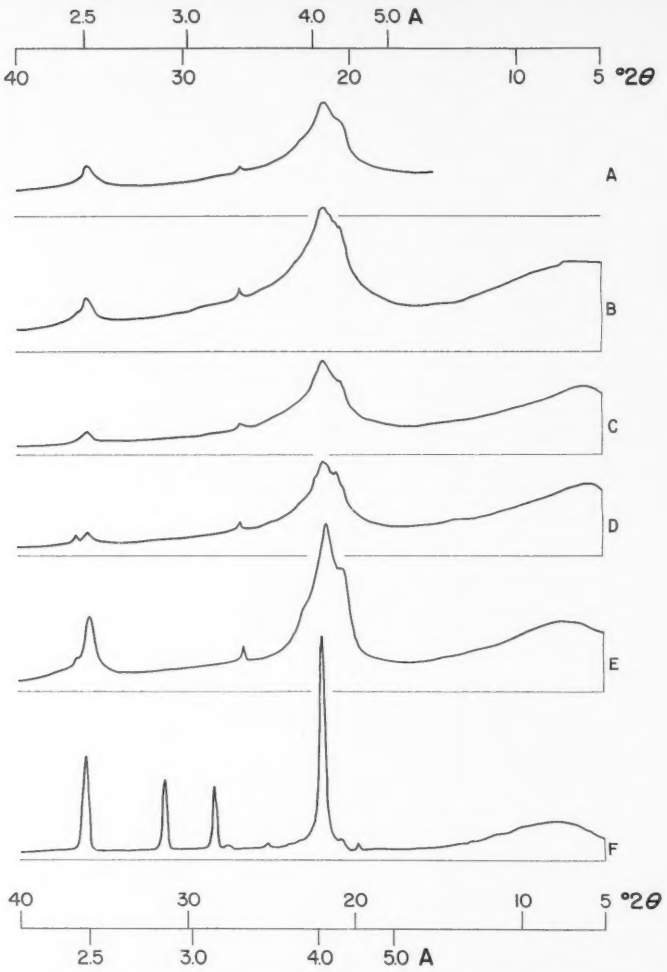

FIG. 5.—Diffractograms of soft opal sample: A) unheated, B) air-dried for 5 months, C) dried at 105°C for 8 hours, D) heated to 300°C ,E) heated at 900°C for 1 hour, and F) heated at 1505 ± 5°C for 5 hours.

Sudo (1955, fig. 1) and by Flörke (1955b, fig. 17).

The diffractogram of the sample of soft opal that was dried in air for 5 months shows general similarity to the pattern obtained from the untreated sample, but does show intensification of the broad peak between 4.8 and 3.7A. In addition, a small shoulder developed at 2.47A on the 2.51A peak.

Drying the samples at 105°C for 8 hours produced no major changes in the opal that could be detected in the diffraction patterns. Heating the samples to 300°C and cooling

them rapidly in air produced no major changes except for slight intensification of the peak between 4.8 and 3.7A and better definition of the weak reflections at 4.31 and 4.11A. The trace of the sample of hard opal heated to 300°C also shows better definition of the shoulder at 2.47A; a small peak appeared in the soft opal trace at 2.46A.

Diffractograms prepared after heating the samples to 900°C for 1 hour and cooling them rapidly in air show all reflections markedly intensified except for the shoulder reflections at 2.47A and the quartz reflections at 3.35A. The quartz reflections at 4.27A can not be distinguished. The hard opal heated to 900°C also gave a reflection at 2.86A.

The hard and soft opal samples were heated further to 1505 ± 5°C; heating required 38 hours; the samples were maintained at this temperature for 5 hours; cooling required 72 hours. The X-ray patterns obtained are those for well-ordered low-cristobalite and alpha-tridymite. The low-cristobalite reflections are very much stronger than the tridymite reflections and are at 4.48A (19.8° 2θ) (101 beta), 4.06A (21.9° 2θ) (101), 3.14A (28.4° 2θ) (111), 2.85A (31.4° 2θ) (102), and 2.49A (36.0° 2θ) (200). Weak but distinct alpha-tridymite reflections are apparent at 4.31, 3.53, 3.22, and 2.98A (20.6, 25.2, 27.7, and 30.0° 2θ) in the diffractogram of the hard opal sample. All these reflections except the 2.98A tridymite reflection are present, but weaker, in the soft opal diffractogram. The weakness of the tridymite reflections indicates that the samples were converted mainly to cristobalite. The hard opal yielded more tridymite on intense heating than did the soft opal.

DISCUSSION

The literature contains numerous references identifying the components of opal as being high- or low-cristobalite, or both, as as having X-ray reflections at or near 4.1 and 4.3A (e.g., Levin and Ott, 1933; Neuwirth, 1940; Fenoglio and Sanero, 1943; Raman and Jayaraman, 1953a; Sudo, 1950, 1956). Raman and Jayaraman (1953b) modified their earlier 1953 conclusion later in the same year and concluded that the opal they examined contained high-cristobalite and tridymite.

Recent work by Flörke (1955 a, 1955 b) indicates that some opal is a disordered form of low-cristobalite whose structure yields an X-ray reflection at 4.1A, about the same position as high-cristobalite. He concludes that the disorder is accomplished by periodic interstratification of SiO_2 tetrahedral layers having a tridymite structure that produce reflections at or about 4.3A. The present writers noted that the 4.3A reflection may be masked by quartz reflections at 4.27A and can be overlooked easily in samples containing abundant quartz as in sample 7, table 5.

Buerger (1954) concludes that tridymite is not pure SiO_2, but that it may have a chemical composition approximating $NaCaAl_3Si_{15}O_{36}$ (Buerger and Lukesh, 1942). According to Flörke, foreign cations (e.g., Na^+, Ca^{+2}, and Al^{+3}) distort the cristobalite lattice and force local development of tridymite structure. The limited, stuffed structure of tridymite postulated by Buerger is thought by Flörke to cause disordering of the cristobalite lattice, and the tridymite reflections at 4.3A are thought to be obtained from a substance that is an integral part of the opal structure and not a separate crystalline phase. Flörke, therefore, concludes that the classic concepts of the SiO_2 system as presented by Fenner (1913) no longer are valid. A review of Flörke's 1955b paper is available in English (Eitel, 1957).

All opal samples studied in conjunction with this report (with the one exception of the diatomaceous marl) have X-ray characteristics similar to those attributed by Flörke to low-cristobalite disordered by tridymite layers (table 5). The diffractograms of the samples of hard and soft opal that were heated to 1505°C and the chemical data lend further support to his concept, inasmuch as the samples recrystallized into well-ordered and distinct low-cristobalite and low-tridymite phases. The chemical data demonstrate that the opal is not pure SiO_2; but that it contains foreign cations including, among others, sodium, potassium, calcium, and aluminum. Therefore, in accordance with Flörke's work, the reflections obtained from the unheated opal at 4.31 and 2.47A are attributed to interlayered low-tridymite, and the stronger reflections at 4.11 and 2.51A are attributed to disordered low-cristobalite.

TABLE 5.—*Angstrom values of reflections from various opal samples from the Ogallala Formation*

1	2	3	4	5	6	7	8
—	12b O	12b O	12b O	13b O	14b O	14b O	10b O
						6.51w F	5.65w F
4.31m O	4.31m O	4.31m O	4.31s O	4.31s O		4.31w O	4.31s O
			4.27w Q			4.27m Q	4.27w Q
4.11s O	4.11s O	4.11s O	4.11s O	4.11s O		4.11w O	4.11s O
					4b O		
			3.86w C				3.86w C
						3.78w F	
3.35w Q	3.35w Q	3.35w Q	3.35m Q	2.35w Q	3.35m Q	3.35s Q	3.35s Q
		3.24w F				3.25m F	3.25w F
			3.21w F			3.21w F	3.21w F
			3.04s C				3.04s C
							2.99w F
							2.57w F
2.51w O	2.51w O	2.51w O	2.49m O	2.51m O		2.15? O	2.51m O
2.45? O,Q	2.45? O,Q	2.46w O,Q	2.45w O,Q			2.46w O,Q	2.46w O,Q
			2.28w Q			2.28w Q	2.28w Q

b, broad band; w, weak; m, moderate; s, strong reflections. O, opal; C, calcite; F, feldspar; Q, quartz. Column 1, soft opal from Kimball Member, Ogallala Formation, sec. 5, T. 16 S., R. 34 W., Scott Co., Kansas; column 2, same sample heated to 105°C for eight hours; column 3, hard opal shell surrounding soft opal from Kimball Member, Ogallala Formation, sec. 5, T. 16 S., R. 34 W., Scott Co., Kansas; column 4, opaline "chert" from Kimball Member, Ogallala Formation, St. Jacobs well, sec. 24, T. 32 S., R. 25 W., Clark Co., Kansas; column 5, opaline "chert," Kimball Member, Ogallala Formation, sec. 16, T. 4, S., R. 36 W., Rawlins Co., Kansas; column 6, diatomaceous marl, Ash Hollow Member, Ogallala Formation, sec. 11, T. 11 S., R. 38 W., Wallace Co., Kansas; column 7, opal-cemented sandstone, Valentine Member, Ogallala Formation, sec. 21, T. 3 S., R. 12 W., Smith Co., Kansas; column 8, opal-cemented siltstone, Valentine Member, Ogallala Formation, sec. 24, T. 5 S., R. 19 W., Phillips Co., Kansas.

Differential thermal and chemical analyses of the hard and soft opal also are in accord with work by Flörke (1955b). The endothermic reactions at 170°C in the hard opal and at 200°C in the soft opal are similar to reactions obtained by Flörke from what he regarded as disordered low-cristobalite. According to Flörke, the endothermic reactions represent inversion points or structural transformations; therefore, the greater the degree of disorder, and likewise the concentration of contained cations, the lower the temperature of inversion. The hard opal, which contains the greater amounts of K^{+}, Na^{+}, Ca^{+2}, Al^{+3}, etc., has its first major endothermic reaction, presumably a structural transformation, at a lower temperature than does the soft opal.

Therefore, it seems that the hard and soft opal studied in conjunction with this report conform in structural and chemical properties to the interpretations advanced by Flörke, and that their differences in hardness cannot be attributed to differences in structure and cation content but that they relate to water content. The weight-loss studies show that the soft opal contains more water than does the hard. The amplitude of the differential thermal analysis curve of the soft opal is greater than that of the hard opal. This fact supports the conclusion that the soft opal contains more water than does the hard opal.

Iler (1955, p. 233–247) discusses adsorbed water on surfaces of so-called amorphous silica and points out that some of the water is physically adsorbed, whereas the rest seems to be bound to the silica surfaces as hydroxyl groups ("bound water"). The physically adsorbed water is lost on heating at 115°C. Water lost above 115°C is bound water and comes from dehydration of surface hydroxyl groups. Figure 2, which shows cumulative weight-percent water lost by hard and soft opal samples, indicates that the soft opal contains more bound water than does the hard.

Although structural disorder due to cation content is not as great in the soft opal as it is in the hard opal, comparison of the diffractograms shows that definition of the disordered low-cristobalite peaks at 4.3, 4.1,

2.51, and 2.47A is not as good in patterns from soft opal as it is in patterns from hard opal. Seemingly the degree of crystallization is not as high in the soft opal as it is in the hard, and the soft opal is more disordered than the hard opal owing to the bound water content of the former. According to Iler (1955, p. 235) the bound water content depends in turn on the surface area of the gel.

ORIGIN OF MASSIVE OPAL

The presence of opal and related siliceous rocks in arid regions and, in general, peneplained regions of sporadic rainfall has been long recognized. The siliceous rocks (silcretes) of South Africa are an example (Lamplugh, 1907). Williamson (1957) recently has described similar silicified rocks from the northern part of South Australia. In Kansas the abundant opal in the upper part of the Kimball Member of the Ogallala Formation is believed to have been deposited by downward-percolating vadose water during the period of extreme aridity that produced the capping caliche (pisolitic limestone) at the close of Pliocene time (Frye, Leonard, and Swineford, 1956, p. 20, 63). Frye and Leonard (1957, p. 9) describe the erosional-depositional hiatus between the Pliocene and Pleistocene as "the culmination of the trend toward aridity." On the basis of both paleontologic and lithologic evidence, they conclude that:

> conditions on this stable surface were at least as dry and unfavorable to organic life as are those of the present. In fact, it seems likely that the generally featureless surface, low regional water table and resultant scarcity or lack of permanent streams, and the almost universal surficial blanket of caliche coming at the end of a long period of increasing dryness denote the most adverse conditions to plant and animal life of any time during the Cenozoic.

It is proposed that leaching of the Kimball Member (which is everywhere rich in feldspar and quartz) freed SiO_2, Na, K, Ca, Al, etc., which were redeposited as opal having a disordered low-cristobalite structure like that described by Flörke (1955a, 1955 b). Ample opportunity for inclusion of Na, K, Ca, and Al in the opal is afforded. Swineford, Frye, and Leonard (1958) present evidence for destruction of both feldspar and quartz by the soil-forming processes that produced the overlying pisolitic limestone, in which quartz and feldspar, both sodic and potassic, are extensively replaced by calcium carbonate. In addition, deposition of the opal in a "mortar bed" host at the expense of the host probably liberated additional cations that could have been incorporated in the opal.

The soft opal, which is preserved in the centers of joint blocks in the massive opal, probably retains greater amounts of water than does the surrounding hard opal because drying has been inhibited by the surrounding rock.

CONCLUSIONS

Massive opal in the Kimball Member of the Ogallala Formation is composed of hydrated low-cristobalite that is disordered by differing amounts of low-tridymite, which forms an integral part of the opal structure. The development of tridymite structure in the opal is due to incorporation of cations (e.g., Na^{+}, K^{+}, Ca^{+2}, and Al^{+3} among others) in the low-cristobalite structure. It is proposed that leaching of the Kimball Member, which is everywhere rich in feldspar and quartz, during formation of the capping caliche (pisolitic limestone), freed SiO_2, Na^{+}, K^{+}, Ca^{+2}, and Al^{+3}, which were redeposited as opal having a disordered low-cristobalite structure like that described by Flörke (1955 a, 1955 b). Differences in hardness of opal samples seemingly are due to differences in water content; the more hydrated samples have lesser hardness.

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FIGS. 1–6, JUNE, 1959

EFFECT OF SIZE AND GENETIC QUARTZ TYPE ON SPHERICITY AND FORM OF BEACH SEDIMENTS, NORTHERN NEW JERSEY[1]

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ABSTRACT

Sphericity has been determined on quartz grains from beach sediments of northern New Jersey to determine its variation with size and genetic quartz type in a beach environment. Within the size range studied, -5ϕ to $+4\phi$, sphericities increased from a minimum of .59 at -4.5ϕ (22 mm) to a maximum of .85 at $+0.9\phi$ (0.55 mm), and then decreased again to .76 at $+3.4\phi$ (0.10 mm).

It appears certain that both size, as such, and genetic quartz type, influence sphericity values; but their relative importance is uncertain. The size range in which the control of quartz type on sphericity appears best developed and most noticeable is between -1.5ϕ and $+1.0\phi$. In coarser grains, either sphericity when released from the parent rock, or mode of abrasion, seems to assume greatest importance. Coarser sizes consist very largely of vein quartz, which may have an inherently low sphericity. In finer sizes, sphericity decreases, apparently independently of quartz type.

Comparison with river pebbles from both the Aftonian Bridgeton Formation in northern New Jersey, and the present Colorado River (Texas) sediments, indicates that the beach pebbles tend to be more discoidal, and the fluvial pebbles more rod-like, in sizes coarser than -2.5ϕ (about 6 mm). In gravel sizes finer than this, grains from the two environments are apparently indistinguishable by form. Sand grains of the beach samples studied have a rod-like tendency.

INTRODUCTION AND PREVIOUS WORK

Many past studies of sphericity in fluvial or marine sediments have not given sufficient emphasis to the following factors:

(1) Although the various rock types supplied by the source area were noted, these were not separated in sphericity calculations.

(2) Particle size has been imperfectly controlled, or only a very small size range has been studied.

Perhaps the most common and severe fault of previous studies has been (1), above. The typical study of grain spericities has failed to bring out the fact that various rock types and mineral grains have inherently different sphericities. In addition, it apparently has been assumed that all rock and mineral types will show the same shape responses to conditions existing in the transporting medium. This has produced two results:

(1) The effects of different transporting media have been concealed.

(2) Effective comparison with the results of other shape studies has been precluded because of lithologic variations.

A sphericity analysis that has been free from the above defects is a study by Sneed and Folk (1958) dealing with Colorado River (Texas) pebbles. They used a new measure, *maximum projection sphericity*, and a triangular plot for analyses of 3-dimensional form. This new technique was also used by Mason (1957), who analyzed sphericities of quartz grains on Mustang Island, a Texas Gulf Coast barrier bar, in the $+2.5\phi$ to $+3.25\phi$ size range. Unfortunately, both of these studies were restricted to a narrow size range. In fact, Mason's size coverage of only 0.75ϕ prevented him from noting any change in sphericity values with size. Sneed and Folk did find a regular decrease in sphericity of progressively larger quartz pebbles from .75 at -3.5ϕ to .66 at -6.0ϕ. However, neither of these two investigations split the quartz into separate groups for individual sphericity analyses of each quartz type. Later examination showed that the quartz in Mason's sediments is largely of the "common" type (as defined in a later part of this paper), while that of Sneed and Folk's study is chiefly metaquartzite and vein quartz.

It is the purpose of this study to analyze the sphericity and form variation of quartz grains in a continuous size range from large pebbles to fine sand in a littoral environ-

[1] Manuscript received August 22, 1958.

ment. As in past sphericity studies, it is here assumed that the parameters studied are reflecting the influence of their present environment, and have not retained the shape characteristics of previous depositional environments to a significant degree. Quartz was selected for study because, volumetrically, it is probably the most important mineral in sand or gravel size sediments. The ocean beach at Long Branch, New Jersey, was chosen as the sampling site because it was composed almost exclusively of quartz sand and gravel (Blatt, 1958), ranging in size from -5ϕ to $+4\phi$. Unfortunately, the amount of each of the three major genetic quartz types (vein, metamorphic, and granitic) varied widely between adjacent size groups, a situation not realized at the start of the study. This fact rendered it difficult to evaluate separately the effect on sphericity of quartz type as opposed to that of size change as such.

PROCEDURE

Two poorly sorted sandy gravel samples from Long Branch were selected to be analyzed because each sample contained a large number of grains in all phi sizes between -4ϕ and $+4\phi$. Each sample was sieved at a one phi size interval for fifteen minutes on a Ro-tap machine, and the grains on each sieve were then divided into two parts and bottled. This procedure yielded 4 bottles of grains for each whole phi interval between -4ϕ and $+4\phi$. An exception was made with the grains on the $+4\phi$ screen, all of which were taken from two samples but put in one bottle.

The bottles were then given new random code numbers and measured in random order to preclude the possibility of the operator measuring all grains of one size on a day when he might estimate fractional measurements either consistently larger or smaller than their true value. Fifteen quartz grains from each bottle were measured at different times; these were summed to a total of 60 grain sphericities within each one phi size range (with the exception of the $+3\phi$ to $+4\phi$ size, in which only 47 grains were measured).

The mean size of the grains within each phi interval was obtained by taking the amount within each one phi size range from the gross sediment sample as plotted on cumulative probability paper, recomputing this portion of the curve to 100%, and calculating its mean size. This was done to eliminate error arising from the fact that mean and median are not coincident in the sediment from a one phi interval obtained from the "tails" of a larger frequency distribution. For example, if a Gaussian curve has a mean size of 1.00ϕ and a standard deviation of 0.60ϕ, the mean size of the sediment between $+2\phi$ and $+3\phi$ is not $+2.5\phi$, but approximately $+2.2\phi$.

In addition, eleven lag gravel samples obtained at Long Branch were measured in order to obtain 32 pebbles in the -5ϕ to -4ϕ range. Fluvial pebbles from the Aftonian Bridgeton Formation obtained by the writer from a gravel pit near Allanwood, New Jersey were measured in sizes between -5ϕ and -2ϕ.

Due to the wide size range studied, both vernier caliper and microscope were used in the sphericity measurement procedure, expediency dictating the use of the microscope for grains finer than 0ϕ. Each grain coarser than this size was measured with the caliper using the method described by Krumbein (1941, p. 65–66).

The finer grains were scattered on a black micropaleontology grid and the grid was tapped until the grains rested with the plane of maximum projection lying horizontal. Two of the dimensions (longest and intermediate) were measured using a micrometer eyepiece, and the third dimension was measured by focusing on the bottom of the grain and then raising the microscope tube until the top of the grain came into focus. A vernier on the fine focusing knob was read to determine the height (short axis) of the grain.

From these data the ratio of the short axis to the long axis (S/L), and the ratio of the long minus the intermediate to the long minus the short (L−I/L−S) were computed. These values were then plotted on triangular diagrams (figs. 1, 2, and 3) from which both maximum projection sphericity and form can be read directly, following the method of Sneed and Folk (1958).

After all sphericity and form measurements had been made, the grains from each phi interval were mounted in plastic and

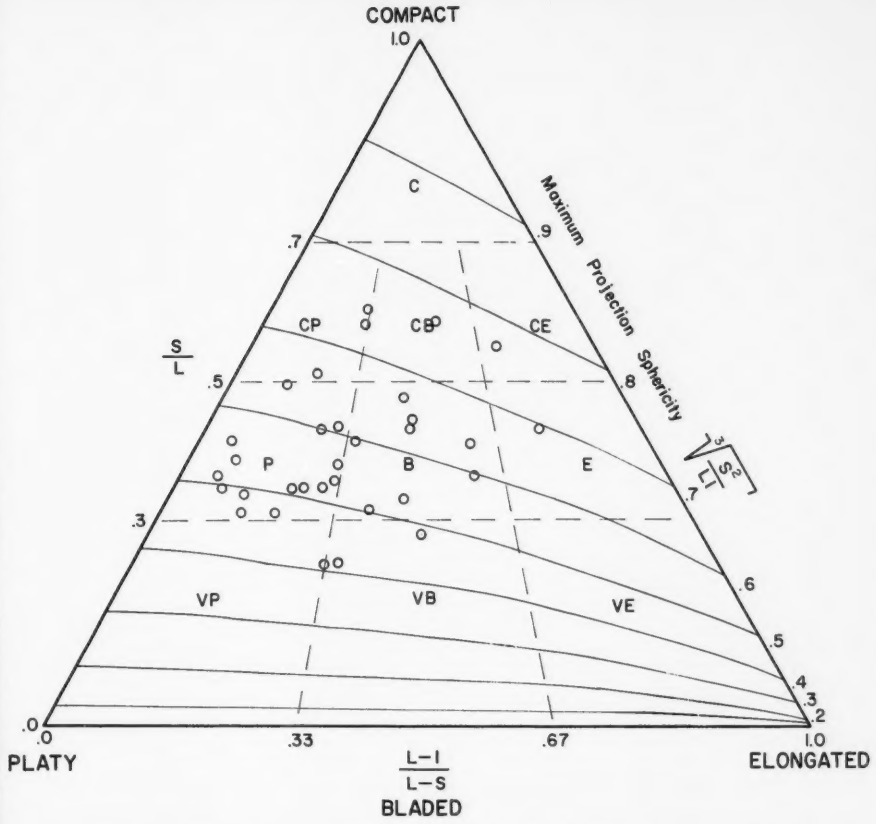

FIG. 1.—Sphericity-form diagram for quartz pebbles in the -5ϕ to -4ϕ size range, which is all vein-derived. The method of plotting form is that of Sneed and Folk (1958). Long, intermediate, and short axes of the particle are designated respectively L, I, and S; points are plotted by using ratios of these dimensions shown on the left and bottom sides of the triangle. Sphericity is shown by the lines curving to the lower right. Each point represents a single pebble. Observe the low mean sphericity and strong platy (disc-like) tendency—i.e., the pebbles tend to fall on the left side of the form triangle.

thin-sectioned, one phi size being used on each slide to avoid the possibility of small fragments of larger grains being mistaken for whole grains of a finer size. In each size group, 100 grains were counted to determine the change in percentage of each genetic quartz type with size. Three quartz types were defined as follows:

(1) Common quartz—Single crystallographic units with straight or slightly undulose extinction; few vacuoles.

(2) Metamorphic quartz—(a) Moderately- to strongly-undulose extinction; grains generally composed of many sub-individuals but this type also includes highly strained single quartz crystal units; or (b) composite, recrystallized quartz, with sub-individuals having straight extinction but different extinction angles.

(3) Vein quartz—Abundant vacuoles; often shows well developed comb structure. Highly strained yet very bubbly grains were

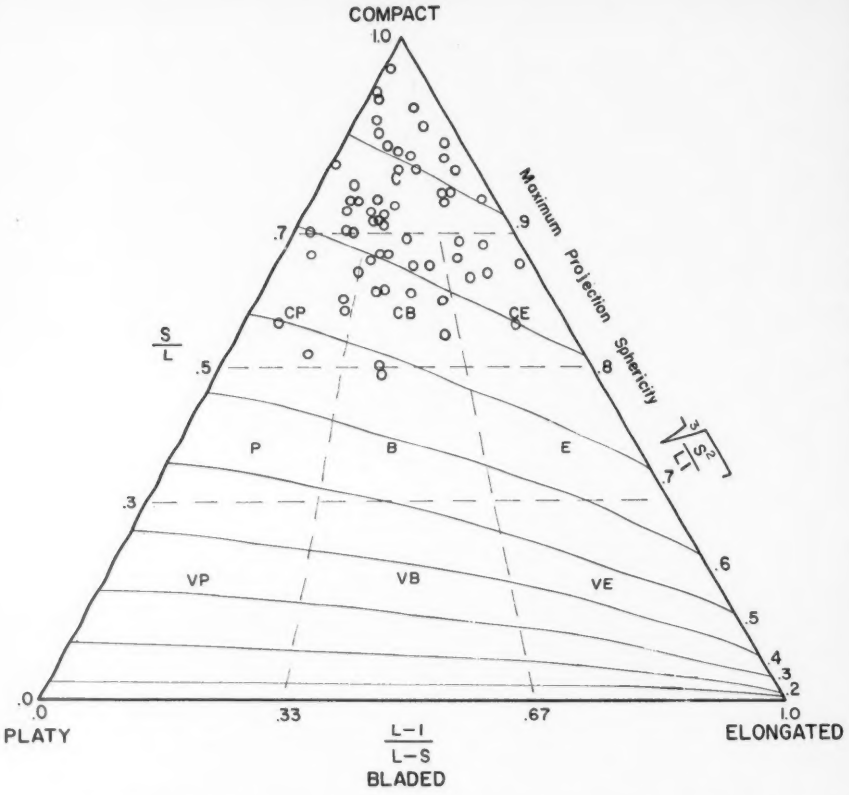

FIG. 2.—Sphericity-form diagram for quartz in the 0ϕ to +1ϕ size range. Extreme compactness of form and high mean sphericity are evident.

tabulated as vein quartz; however, this strained type comprised less than 10% of all vein quartz.

GENETIC QUARTZ TYPE AS A FUNCTION OF SIZE

Figure 4 shows the close relation between quartz type and grain size. Grains coarser than −2ϕ are almost entirely vein quartz; slowly diminishing amounts are found in finer sizes until it virtually disappears at +1ϕ. This is readily apparent to the naked eye because almost all grains coarser than −2ϕ are milky, while the sands contain only a very few milky grains. This change was verified by crushing grains and examining them in oils. Metamorphic quartz is present in small amounts throughout most of the size range studied, but is most prevalent between −2ϕ and −1ϕ, where it forms up to 40% of the total sample. Common quartz appears at −2ϕ, rapidly increases in abundance with decreasing size, and strongly dominates the sample in all sizes finer than 0ϕ.

The size ranges in which these quartz types appear are almost certainly a function of the size of quartz grains liberated from the source rocks. Veins provide the coarsest grains, and granites (the main contributor to the "common" quartz type) generally yield the smallest quartz in the area studied.

SPHERICITY VERSUS SIZE

Sphericity shows significant changes between the different size grades (fig. 4 and table 1). The largest pebbles have the lowest sphericities (mean sphericity only .59 at -4.4ϕ); from there sphericity rapidly increases to an apparently asymptotic value of .75 at a size of -2ϕ. At -1ϕ, sphericity again increases, reaching a maximum of .85 at about $+1\phi$. From this point, sphericity values slowly decline to .76 at $+3.4\phi$. Thus highest sphericity values for northern New Jersey beach sediments are attained in the coarse sand to granule range.

CAUSES OF SPHERICITY CHANGES

With present information it is difficult to say whether the changes in sphericity are due to size, as such, or whether they result primarily from genetic quartz type. That is, does sphericity change as a function of size only because the dominant quartz type also changes as a function of size?

The chief factor favoring a sphericity change as a function of pebble size, as such (possibly caused by the nature of the abrasion process) is that sphericity changes for the New Jersey beach sediments parallel the results for other pebble suites as regards sphericity change with size. Unpublished work at the University of Texas has shown, for pebbles of many rock types from several different areas, that for a given rock type sphericity nearly always decreases with in-

TABLE 1.—*Variation with size of sphericity and form of quartz grains from northern New Jersey beach sediments*

SIZE RANGE (MEAN)	MAXIMUM PROJECTION SPHERICITY	$\sigma_{\bar{Y}}$	CONFIDENCE LIMITS (95%) ON M.P.S.	$\frac{S}{L}$	$\frac{L-I}{L-S}$
-5ϕ TO -4ϕ (-4.4ϕ)	.595	.10	$\pm$ .036	.410	.350
-4ϕ TO -3ϕ (-3.4ϕ)	.715	.12	$\pm$ .031	.545	.432
-3ϕ TO -2ϕ (-2.58ϕ)	.745	.11	$\pm$ .028	.565	.518
-2ϕ TO -1ϕ (-1.59ϕ)	.755	.07	$\pm$ .018	.572	.542
-1ϕ TO 0ϕ (-0.46ϕ)	.790	.09	$\pm$ .023	.600	.635
0ϕ TO $+1\phi$ ($+0.56\phi$)	.845	.07	$\pm$ .018	.722	.490
$+1\phi$ TO $+2\phi$ ($+1.38\phi$)	.838	.07	$\pm$ .018	.700	.550
$+2\phi$ TO $+3\phi$ ($+2.16\phi$)	.802	.09	$\pm$ .023	.632	.630
$+3\phi$ TO $+4\phi$ ($+3.40\phi$)	.759	.07	$\pm$ .021	.570	.640

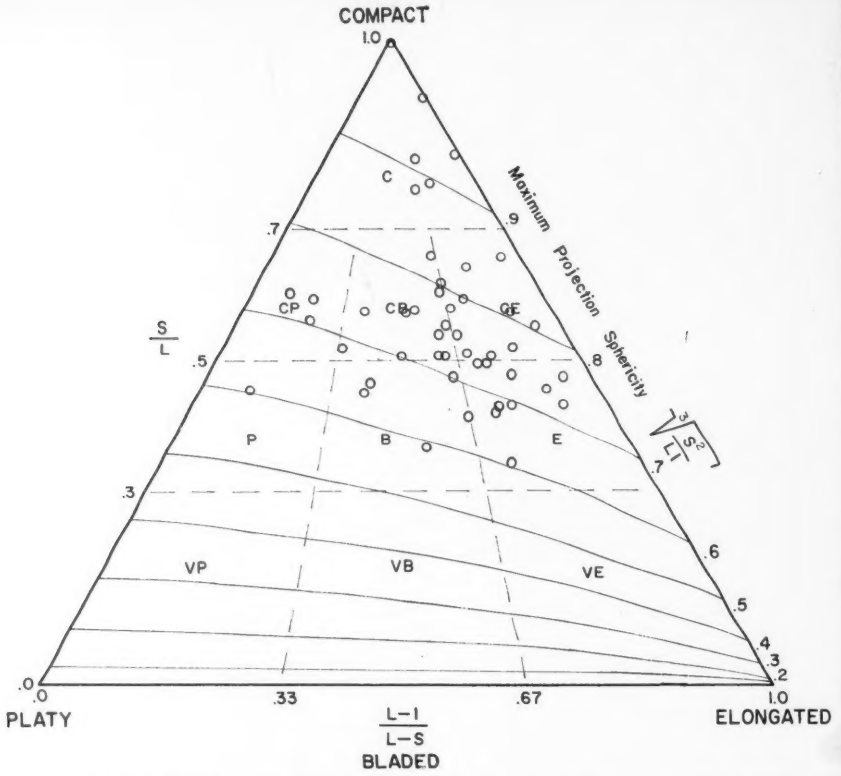

FIG. 3.—Sphericity-form diagram for quartz in the $+3\phi$ to $+4\phi$ size range, which is 95% common quartz. Note moderate sphericity and tendency toward elongate form.

creasing pebble size in the range of -3ϕ to -6ϕ. Sneed and Folk (1958) found for quartz pebbles in the Colorado River at Austin that sphericity decreased from .75 at -3.5ϕ to .66 at -6ϕ.

Pettijohn (1949, p. 401, 404) cites several examples of sand grains (quartz plus various amounts of feldspar) decreasing in sphericity as the size diminishes from $+1\phi$ to $+3\phi$. Thus previous work appears to indicate that sphericity is at a maximum somewhere in the coarse sand to granule range, and decreases in both smaller and larger sizes.

In the present study, it was again found that pebbles decreased in sphericity as their size increased, values ranging from .75 at -2ϕ to .59 at -4.4ϕ. It was also determined that sphericities of sand grains decreased from .85 at $+1\phi$ to .76 at $+3.4\phi$. In both instances, genetic quartz type remained relatively constant over these small intervals.

The chief point favoring genetic quartz type as the main control on sphericity is the anomalous and sudden rise in the sphericity trend between -1ϕ and 0ϕ, which is precisely where vein quartz is superseded by common quartz. It is theoretically probable that vein quartz has a low sphericity because of its comb structure and common evidence of strain. Presumably this anisotropic nature might make it fracture into

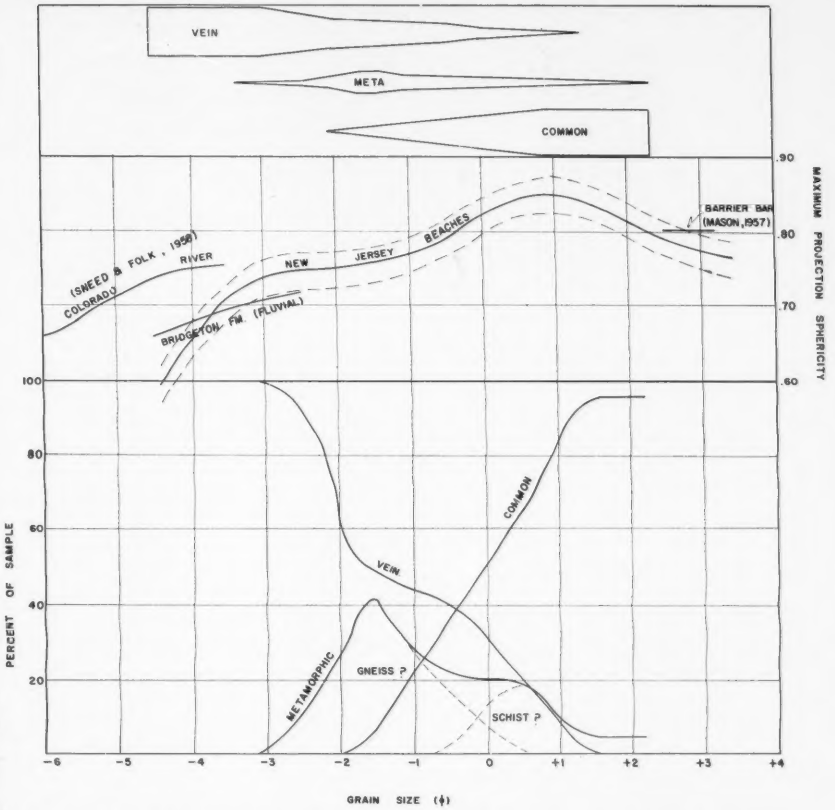

FIG. 4.—Sphericity versus size and genetic quartz type. The rise to dominance of common quartz between -1ϕ and $+1\phi$ may be related to the shape increase in mean sphericity within the same size range. The dashed lines indicate confidence limits at the 95% level on the New Jersey sphericity-size trend.

fragments of inherently low sphericity. Common quartz, on the other hand, generally has fewer well defined planes of weakness due to its formation in a more isotropic environment. Thus it should have a higher inherent sphericity.

Consequently, the upward bend in the sphericity curve at -1ϕ might be interpreted as follows: vein quartz grains reach their highest limiting sphericity of about .75 between -2ϕ and -1ϕ. At this size, common quartz begins to appear in abundance, immediately increasing the sphericity again. At $+0.5\phi$, almost all the quartz is common quartz with a high sphericity value of .85. The sphericity value of .79 at -0.5ϕ could be interpreted as a mixture of half vein quartz grains with a sphericity value of .75, and about half common quartz grains with sphericity about .85. The metamorphic quartz is present in too small a quantity to affect the curve appreciably, and it appears to have about the same low sphericity as vein quartz, also presumably because of formation in an anisotropic environment.

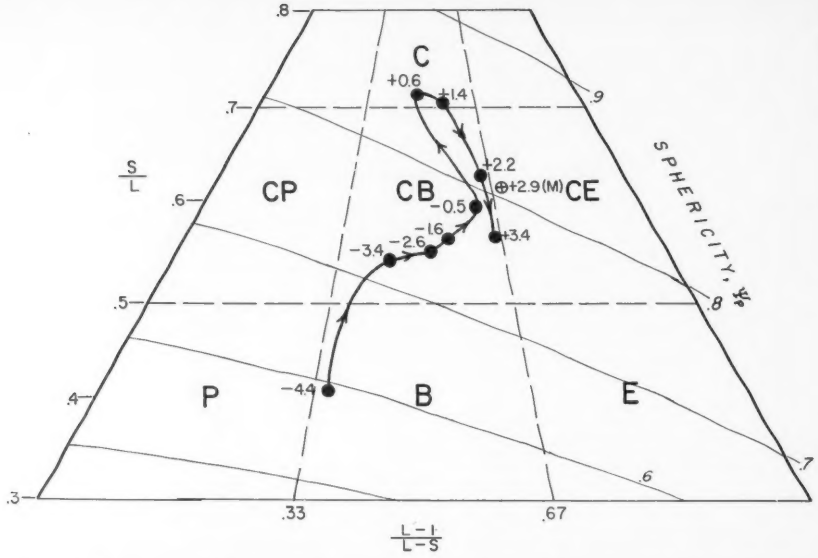

FIG. 5.—Change of sphericity and form within each one phi unit size interval for northern New Jersey beach sediments. Only the central portion of the form-sphericity triangle of figures 1 to 3 is shown here. Each point corresponds to the mean form of a suite of pebbles or grains within one phi size interval; average phi size of the particles within each interval is appended to the points. Mean forms are computed by the method of Sneed and Folk (1958, p. 143). The track connects the points in order of decreasing grain size. Note that sphericity is lowest for the largest pebbles, and reaches a maximum at about $+0.5\phi$ to $+1.5\phi$ (.35 to .70 mm). Sphericity then decreases into the finer sand ranges. The larger pebbles tend to be platy (disc-shaped) because they fall on the left side of the diagram, while the fine and very fine sand grains tend to be elongate (rod-shaped), because they fall on the right side of the triangle. The sudden sidewise jump between -0.5ϕ and $+0.6\phi$ coincides with the change from dominant vein quartz in the coarser sizes to dominant common quartz in the finer sizes, the common quartz apparently having a higher inherent sphericity. The symbol designated (M) represents the mean form of fine sand grains from Mustang Island, Texas, a barrier bar studied by Mason (1957).

FORM CHANGE WITH SIZE

The New Jersey beach pebbles have a discoidal form, which is most pronounced in the larger sizes (figs. 1 and 6). Sneed and Folk's river pebbles, although slightly coarser than those obtained in the present study and hence not strictly comparable, tend to be more rod-like. This rod-like tendency of river pebbles is further verified by the Bridgeton Formation fluvial pebbles within the same size range as the New Jersey suite and probably coming from approximately the same source as the New Jersey beach pebbles. This is apparently a direct reflection of the contrasting types of abrasion prevalent in the two environments. Wave swash on the upper part of a beach slope (where the coarser materials are deposited) tends to produce a sliding motion. This type of movement should generate disk shapes from more spherical shapes by continual abrasion and sliding on a plane normal to the direction of the pebble axis which is initially the shortest. There may be a correspondence between this initially short axis and the anisotropy of the quartz type concerned. In the larger pebbles, the gross fracture pattern in the parent rock (i.e., jointing, exfoliation) may be a significant factor.

River action is essentially turbulent as far as pebble movement is concerned, and

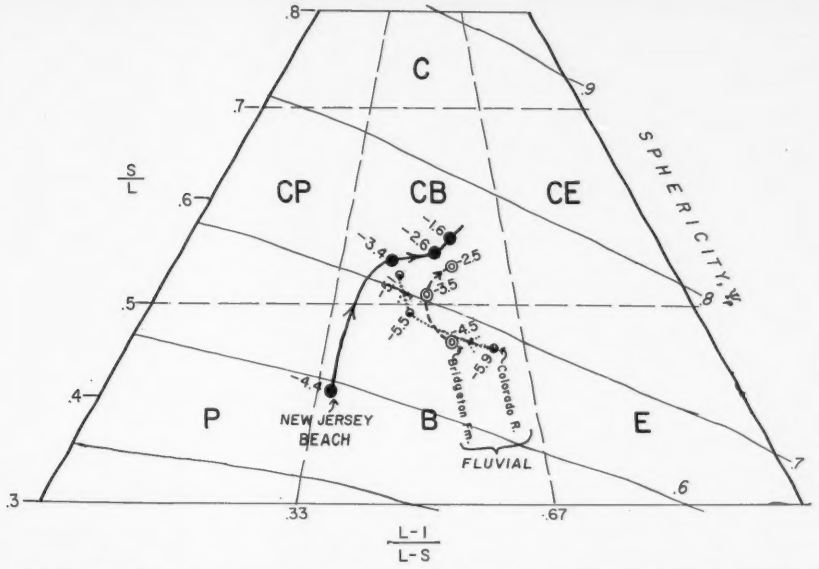

FIG. 6.—Sphericity and form of quartz pebbles of different sizes from several areas. As in figure 5, only the central part of the sphericity-form triangle is shown here, and each point represents the mean form of a suite of pebbles whose average phi size is appended to that point. The tracks connect the points in order of decreasing size. On the northern New Jersey beach, pebbles larger than about -4ϕ (16 mm) show a distinct platy or discoidal tendency in that they fall on the left side of the form triangle. Two sets of river pebbles are shown: a set from the fluvial Bridgeton Formation, also from northern New Jersey, and a set from the Colorado River, Texas (data from Sneed and Folk, 1958). Both sets of river pebbles show an elongate (rodlike) tendency for the larger pebbles. This pronounced difference in form between beach and river pebbles over a certain size may be a helpful diagnostic criterion. Observe also that for all pebble suites, the larger pebbles have lower sphericities.

movement of this size particle is consequently obtained by rolling action, yielding a more rod-like form than is possible in the littoral environment. This rod-like tendency seems to be reduced as the pebble decreases in size and becomes more likely to be transported by saltation. Size decrease and accompanying tendency to saltate also causes the loss of discoidal shape in beach pebbles. River and beach pebbles are apparently indistinguishable by form in sizes finer than -2.5ϕ.

Figures 2, 3, and 5 reveal a strong tendency for quartz grains finer than $+1.5\phi$ in the beach environment to fall into the compact-bladed classification, near the border of compact-elongate. A similar rod-like form was characteristic of Mason's (1957) fine beach sand on the Texas coast. This form suggests that fracturing parallel to the c-axis may be a prominent method of size reduction in sand size particles (Wayland, 1939; Borg and Maxwell, 1956).

FORM AND GENETIC QUARTZ TYPE

The location of the sizes at which metaquartz and common quartz are introduced is strikingly shown in figure 5. It appears that metaquartz, although having approximately the same sphericity as vein quartz at -2.5ϕ, is conspicuously more rod-like in form. Its point of introduction at -3ϕ produces an abrupt form change due to a relative increase in the length of the long axis as compared with vein quartz. This presumably results from the greater differential which shear metaquartz undergoes during its genesis. However, metaquartz is

not present in abundance, and its reduction to a minor part of the total sample after its mode at -1.5ϕ results in a gradual form change to more compact.

The effect of common quartz is distinctive the mean quartz form (fig. 5) becoming abruptly more compact between -0.5ϕ and $+0.6\phi$. The fact that this form is present at $+0.6\phi$ in a 65% common quartz-10% vein quartz-15% metaquartz mixture testifies to the extremely compact form associated with common quartz.

It seems that the form of New Jersey beach sediments is more severly affected by changes in genetic quartz type than is sphericity.

CONCLUSIONS

The quartz sphericity data obtained in this study suggest the following:

1) Original sphericities of vein, metamorphic, and common quartz are probably strongly influenced by relatively large scale stress phenomena such as jointing, faulting, sheeting, or exfoliation;

2) Final sphericities of each quartz type probably result from a number of factors, among which are:

a) the large scale stress factors noted in (1) above;
b) time, which tends to conceal or remove the effect of (a);
c) size of grain;
d) genetic quartz type;
e) method of size reduction, especially applicable in the finer sand ranges, (this includes the varying effects of the river vs. the beach environments);
f) miscellaneous factors such as bubble train lineations with the grain;

3) In the pebble sizes, transportational or depositional environment may be indicated by the form of the pebbles, those from a river tending to be more rod-like than those affected dominantly by littoral processes of abrasion, which tend toward disks. With regard to pebbles affected by both environments (i.e., river transportation and littoral deposition), time in each environment is certainly a factor in determining the final form of the buried particle; and,

4) The form of sand size quartz grains seems to be very sensitive to changes in genetic quartz type.

ACKNOWLEDGEMENTS

This study formed a part of a thesis submitted by the author (Blatt, 1958) in partial fulfillment of the requirements for the Master of Arts degree at the University of Texas. The thesis was supervised by R. L. Folk; S. E. Clabaugh and R. E. Lane also served on the thesis committee and offered helpful suggestions. The writer is also indebted to S. P. Ellison, Jr. for critical reading of the manuscript and to E. J. Dasch for assistance in drafting the figures.

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FIGS. 1–2, JUNE, 1959

THE MINERALOGY AND TEXTURE OF BEACH SANDS OF GALVESTON ISLAND, TEXAS[1]

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ABSTRACT

Relative proportions of individual heavy minerals in the front- and back-bar beaches of Galveston Island are almost identical and indicate little or no compositional difference between the two beaches. Size distributions of the bulk sands from the two beaches, however, show marked differences. Sands of the back beach contain an excess of fine material over the amount predicted from lognormal curves; sands of the front beach exhibit a deficiency of fine sizes, with the deficiency most pronounced in the intermediate (0.1 mm) range. The distribution curves are apparently the result of selective reworking of origina! shoreline sands. The textural features are controlled by local depositional environments on the bar, but compositional properties are apparently independent of these local environments.

INTRODUCTION

Galveston Island is one of a series of large, elongate, offshore bars which characterize much of the Gulf Coast of Texas. The island, which separates Galveston Bay from the Gulf of Mexico, trends in a northeast-southwest direction and is approximately 30 miles long. A sand beach circumscribes the island and may conveniently be subdivided into a frontal beach on the south side of the island, facing the Gulf of Mexico, and a back-bar beach on the north side of the island, facing Galveston Bay. The present study is concerned with the mineralogy and texture of the beach sands and deals primarily with the size distributions exhibited by the sands on the front- and back-bar beaches.

An extensive bibliography concerning work on recent sediments along the Texas Gulf Coast is given by Shepard and Moore (1955).

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PROCEDURE

Seven samples, spaced at 5-mile intervals, were taken from each side of Galveston Island. Those from the front of the island (facing the Gulf) were labeled 1 to 7, and corresponding samples from the back side were labeled 1a to 7a. All samples were taken at a level about 2 feet below the surface of the beach at a point estimated to be roughly midway between high and low tides. Enough sand to fill a 1-quart container was obtained at each locality.

A 50-gram portion of each sample was selected for sieving and heavy mineral analysis. This material was dried under an infrared heat lamp, disaggregated with a wooden rolling pin, and boiled in a solution of stannous chloride in 2N hydrochloric acid. The average weight loss in acid (caused by removal of carbonate and partial removal of ferruginous material) was about 5 percent.

Heavy minerals were removed from a 5-gram portion of the cleaned sand by centrifuging in bromoform. All samples were initially centrifuged for 5 minutes at approximately 2500 rpm in celluloid centrifuge tubes. The tubes were then placed in crushed dry ice in order to freeze the bromoform, and the bottom part of the tube containing the heavy minerals was severed from the upper part. The heavy minerals were then recovered on filter paper after allowing the bromoform to melt, and were washed with acetone. The light fraction was recentrifuged, and the whole process was repeated twice more. The heavy minerals from each of the three separations were then combined and examined together. The amount of heavy minerals removed in the second and third steps was much less than in the first step, and only an insignificant fraction was recovered

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during the third centrifuging.

The separated heavy minerals were mounted in Canada balsam on glass slides. Relative mineral percentages were determined separately in each half of the slide (under separate cover glasses) by counting 300 grains; see Dryden (1931) for accuracy of such counts. The average percentage of heavy minerals recorded for each sample is the average of both halves of the slide, except in the case of two samples, for which only one count was made. The total weight percentage of heavy minerals in each sample is not accurately known owing to the impossibility of separating inclusion-filled, iron-stained quartz from the true heavy minerals.

The size distributions of the bulk samples (almost entirely quartz) were determined by sieving approximately 30 grams of clean sample from which calcareous and ferruginous matter had been removed. The sieving was done in a conventional RoTap shaker for 7 minutes, and the weight percentages in each size grade were plotted on logarithmic probability paper. All samples were initially analyzed with sieve intervals as shown in table 3. These intervals demonstrated the percentages in the tails of the distribution curves but were not particularly well suited to plotting the central portions of the curves owing to the excellent sorting of the samples. Consequently, eight of the samples were reanalyzed using the sieve intervals shown in table 4.

RESULTS

Table 1 shows the average relative percentages of nonopaque heavy minerals in samples from the front and back beaches of Galveston Island. Obviously, no major differences occur, but in order to test the possibility that the two beaches exhibit slight differences in mineralogy, the abundances of hornblende, zircon, tourmaline, and garnet were subjected to a variance analysis; for discussion of method see Dixon and Massey (1957). The variance analysis was designed to determine whether or not any of the four minerals varied significantly in abundance either parallel to the beaches or from one beach to the other. The various sample pairs were used as columns (a total of 7) and the respective beach samples as rows (a total of 2). The percentage data, being rather small numbers, were normalized by the arcsin $\sqrt{x}$ transformation. The F values obtained are the ratios between the mean squares of the column or row means and the residual. Table 2 shows the F values for row effects (variation between beaches) and column effects (variation along beaches). No significant variation occurs between the front and back beaches of the island except in the case of garnet, and its variation is small. Insofar as the relative proportions of heavy minerals can be considered indicative of the composition of the clastic material in the beach sands, the two beaches appear to be compositionally similar. Non-clastic, or at least locally derived, materials such as shell fragments are slightly more abundant in the back-side beach as shown by the fact that the average total percentage of acid-soluble

TABLE 1.—*Average relative abundances of heavy minerals in the beach sands of Galveston Island*

Mineral	Abundance in front-bar beach	Abundance in back-bar beach
Hornblende	15.8%	15.9%
Zircon	14.9	15.0
Tourmaline	11.0	11.6
Garnet	8.6	7.0
Sphene and Monazite	7.0	5.4
Epidote	5.1	5.1
Kyanite	3.9	3.4
Pyroxene	1.1	1.2
Opaque minerals	30.2	32.1
Others (staurolite, andalusite, rutile, apatite)	remainder	remainder

TABLE 2.—*Results of variance analysis of the relative proportions of hornblende, zircon, tourmaline, and garnet in the front- and back-bar sands of Galveston Island*

Mineral	F-value for variation between beaches	F-value for variation along beaches
Hornblende	0.12	1.09
Zircon	0.015	5.23[1]
Tourmaline	1.08	6.77[1]
Garnet	6.80[1]	1.00

[1] Significant at the 95% level.

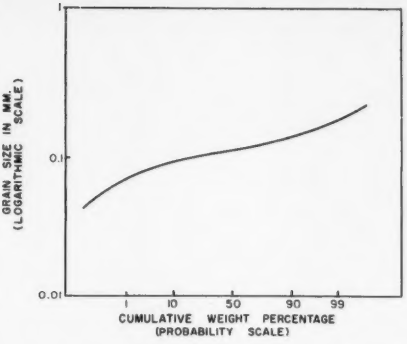

FIG. 1.—Grain size distribution in typical sample of sand from the frontal beach of Galveston Island, facing the Gulf of Mexico.

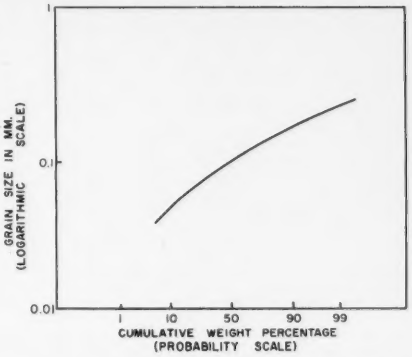

FIG. 2.—Grain size distribution in typical sample of sand from the back beach of Galveston Island, facing Galveston Bay.

material on the back side is 7.5 percent, compared to 3.2 percent in the sand on the front beach, facing the Gulf.

Though the clastic materials on the two beaches are similar in composition, they are quite different in texture. The results of sieve analyses made on the sands of both beaches are given in tables 3 and 4. Table 3 shows the data obtained from a rather widely spaced sieve interval, and table 4 shows the results obtained using a closely spaced interval. On logarithmic probability paper the data from each sample plot in a manner typified by figures 1 and 2, which represent the size distributions in the front- and back-beach samples. The average values of the commonly measured parameters of the size distributions are given in table 5.

As shown in table 5, calculated parameters based on quartiles of the size distribution curves indicate little or no difference between sands of the front and back beaches. Examination of tables 3 and 4 and figures 1 and 2, however, shows that the different beaches contain sands with quite different size distributions. The back-beach sands con-

TABLE 3.—*Results of sieve analyses of cleaned samples of front-bar (1 to 7) and back-bar (1a to 7a) sands from Galveston Island. Results expressed in weight percent of material retained on sieves with the size intervals indicated*

Sample	Mesh sizes in mm.						
	0.420	0.246	0.125	0.062	0.053	0.044	<0.044
1	0	0.06	24.70	75.06	0.08	0.06	0.03
1a	0	0.38	29.39	54.82	3.49	6.02	5.86
2	0	0.82	37.88	61.01	0.16	0.07	0.03
2a	0	1.76	63.98	31.82	1.01	0.74	0.65
3	0	2.77	50.30	46.74	0.13	0.03	0.01
3a	0.02	0.16	31.81	67.34	0.38	0.13	0.11
4	0	0.44	34.70	64.68	0.13	0.02	0.01
4a	0	0.03	28.53	65.40	2.82	1.96	1.23
5	0	0.06	17.48	81.62	0.24	0.05	0.01
5a	0	0.17	41.33	44.88	3.52	5.64	4.42
6	0.01	1.33	51.27	46.41	0.51	0.33	0.10
6a	0	0.89	53.05	35.71	3.92	3.92	2.49
7	0	0.17	28.46	71.18	0.12	0.03	0.01
7a	0	0.04	26.82	68.97	1.30	1.15	1.70

TABLE 4.—*Results of sieve analyses of selected cleaned samples of front-bar (1 to 7) and back-bar (1a to 7a) sands from Galveston Island. Results expressed in weight percent of material retained on sieves with the size intervals indicated*

Sample	Mesh size in mm.						
	0.149	0.125	0.105	0.088	0.074	0.062	<0.062
1	11.81	10.92	46.82	25.09	4.87	0.32	0.13
1a	19.75	11.90	26.40	15.82	9.13	3.40	13.58
3	36.62	14.79	34.45	11.88	1.95	0.16	0.12
3a	15.05	15.06	42.95	19.26	6.43	0.96	0.32
5	6.67	10.98	54.37	23.30	4.02	0.39	0.23
5a	30.85	15.88	23.00	10.00	7.85	2.94	9.44
7	12.74	12.15	44.64	24.42	5.39	0.29	0.20
7a	24.24	12.96	42.69	14.18	2.56	0.47	2.87

tain a long tail of fine material while on the front beach, grains smaller than $\frac{1}{16}$ mm are almost completely absent. In addition, size distribution curves for the sands of the back beach, drawn on logarithmic probability paper, are simply convex upward; curves for the front-beach sands are convex upward in the fine sizes and concave upward toward the coarse sizes. The difference in the textures of the sands on the two beaches is largely in the tails of the size distributions, and consequently standard quartile parameters do not indicate the real difference between them.

Many of the size distribution curves obtained are very close to lognormal curves (straight lines on logarithmic probability paper) either throughout the entire distribution or the major part of it. Slight differences from lognormality, however, can be detected for both front and back beaches. For the sands of the back beach, the size distribution curves, in comparison with lognormal curves, may be considered as exhibiting either an excess of fine material or a deficiency of coarse material. In the sands of the front beach, in comparison with a straight line (lognormal curve) drawn through the central part of the distribution, the actual sands exhibit an excess of both coarse and fine material; the actual curve may, however, be compared with a straight line drawn through the coarse fraction, in which case the entire distribution can be considered as showing a deficiency of fine material, the deficiency being greatest in the intermediate size grades.

The writers are not aware of an *a priori* method of determining the most appropriate of several possible ways of comparing actual and lognormal curves. Possibly all methods are equally valid depending upon the ultimate analysis of the data.

TABLE 5.—*Average size distribution parameters for front- and back-bar sands from Galveston Island. Parameters calculated from quartile measurements*

	Front-bar beach	Back-bar beach
Median	0.118 mm	0.118 mm
Sorting coefficient $\sqrt{Q_3/Q_1}$	1.14	1.15
Skewness Q_3Q_1/M^2	1.02	0.997

CONCLUSIONS

The sand which comprises the Galveston bar is largely reworked clastic material from the near-shore sands which have been deposited along the Gulf Coast of Texas. This original material from which the bar was constructed may be presumed to consist of sands which, in the aggregate, exhibit nearly lognormal size distributions. This conclusion is based on the fact that most common, large-scale, sedimentary processes tend to produce materials with such distributions. Consequently, the slightly non-normal distributions of the sands on the beaches of the Galveston bar demonstrate the selective reworking of various components of these original shoreline sands. The individual distributions are

indicative of the activity of "selective" forces as stated in the terminology discussed by Rogers (1958).

Sands of the front beach, facing the Gulf, have obviously been modified by elutriation of fine material by both wave and wind action. This elutriation process has resulted in the deficiency of fine materials shown by the size distribution curves. The greater deficiency in the middle ranges (about 0.1 mm) than in the extremely fine sizes (0.06 mm) may result from the ability of both wind and waves to move the medium-sized material, whereas only water may be effective in moving the extremely fine particles. It is also likely that the intermediate sizes are moved most readily by water. The relative ease of movement of different sizes of grains has been discussed by Inman (1949). If the lognormal curve is drawn through the central portion of the actual size distribution, thus showing an excess of both coarse and fine material, the same conclusion concerning greater mobility of intermediate sized grains is also reached.

The sands of the back beach (facing Galveston Bay) contain an excess of fine materials in the size range of 0.1 mm and less. This excess presumably results from the addition of fine materials, though the precise source of the sand is unknown. The distribution curves for sands of the back beach could also be explained by removal of the coarse sizes, though this possibility seems unlikely.

Reworking of the shoreline sands to form the Galveston bar has caused textural modifications without accompanying compositional changes. The relative proportions of heavy minerals in the back and front beaches are almost identical. Apparently, textural features of the sediments are primarily influenced by local depositional environment, such as position on the bar; whereas, composition is largely determined by the broad tectonic environment of the Gulf Coast and is only slightly influenced by local features.

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FIGS. 1–3, JUNE, 1959

GRAVELS OF ALAMEDA CREEK, CALIFORNIA[1]

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ABSTRACT

The purpose of this study was to determine if data on the recent sediments of Alameda Creek, Alameda County, California, supported the general observation that the size of stream sediments decreases with increasing distance from the stream's headwaters. Beginning at the stream's headwaters on Valpe Ridge and continuing 18 miles to the town of Niles, consecutively numbered observation stations were set up at mile intervals. At each station the size, rock type, roundness, and sphericity of the maximum-sized boulder were determined. Also at observation stations 2, 5, 7, and alternate stations thereafter, two hundred rocks were measured to determine the size distribution of the gravel. Volume frequency and cumulative percentages were computed from the numerical data.

It was found that the maximum boulder size fluctuates throughout the entire length of the stream studied, but generally decreases as distance from the headwaters increases. The fluctuations seem to be due to constrictions in the width of the stream channel and changes in the stream gradient. The median diameter graph is very similar to the maximum-boulder-size graph. The sediments appear to be well sorted. Sphericity of the maximum-sized boulder fluctuates whereas the roundness increases as the distance from the headwaters increases. In general, the data on recent sediments of Alameda Creek support the observations made on other streams and have no major anomalies.

INTRODUCTION

This report is a study of the recent sediments of Alameda Creek. The object of the analysis was to determine if data on the recent sediments of Alameda Creek supported the general observation that size of stream sediments decreases with increasing distance from the stream's headwaters. It was also made to determine the general nature of the sediment's roundness, sphericity, and sorting, and to determine how these features varied with increasing distance from the stream's headwaters. Width of the stream bed and position of the major tributaries were also considered as minor contributing factors.

Measurements were taken at mile intervals. Size, roundness, and sphericity of the maximum-sized boulders were determined as well as the size distribution and statistical constants of the stream gravel. In terms of the A.G.U. size classification (A.G.U., vol. 28, p. 937), most of the stream sediments range in size from fine gravel to large cobbles, but for the sake of simplicity they will all be referred to as gravel throughout this article.

Very little study of stream sediment size and factors relating to size has been done in the past. Two notable papers on this subject are Krumbein's paper on the flood deposits of Arroyo Seco (Krumbein, 1942), and Plumley's paper on the Black Hills terrace gravels (Plumley, 1948). No work of this type has previously been done on Alameda Creek or other streams in the general vicinity.

AREA STUDIED

Alameda Creek is located in Alameda County, California. Its headwaters are on the crest of Valpe Ridge in the southwest corner of the La Costa Valley, 7.5 minute, Quadrangle. The creek flows northwest through Sunol Valley and then into Niles Canyon. After leaving the canyon, it flows into the Santa Clara Valley and through the towns of Niles and Alvarado. It then empties into San Francisco Bay about three miles north of the Dumbarton Bridge. Figure 1 indicates the general area in which the study was made.

The area covered in the analysis extends from the headwaters of the creek on Valpe Ridge to the town of Niles. This is a distance of approximately 18 miles. Below Niles, the stream is being dredged for flood control purposes. A sediment analysis on this part of the stream was not undertaken because of alteration of the stream's course due to dredging.

In the area studied, the stream predomi-

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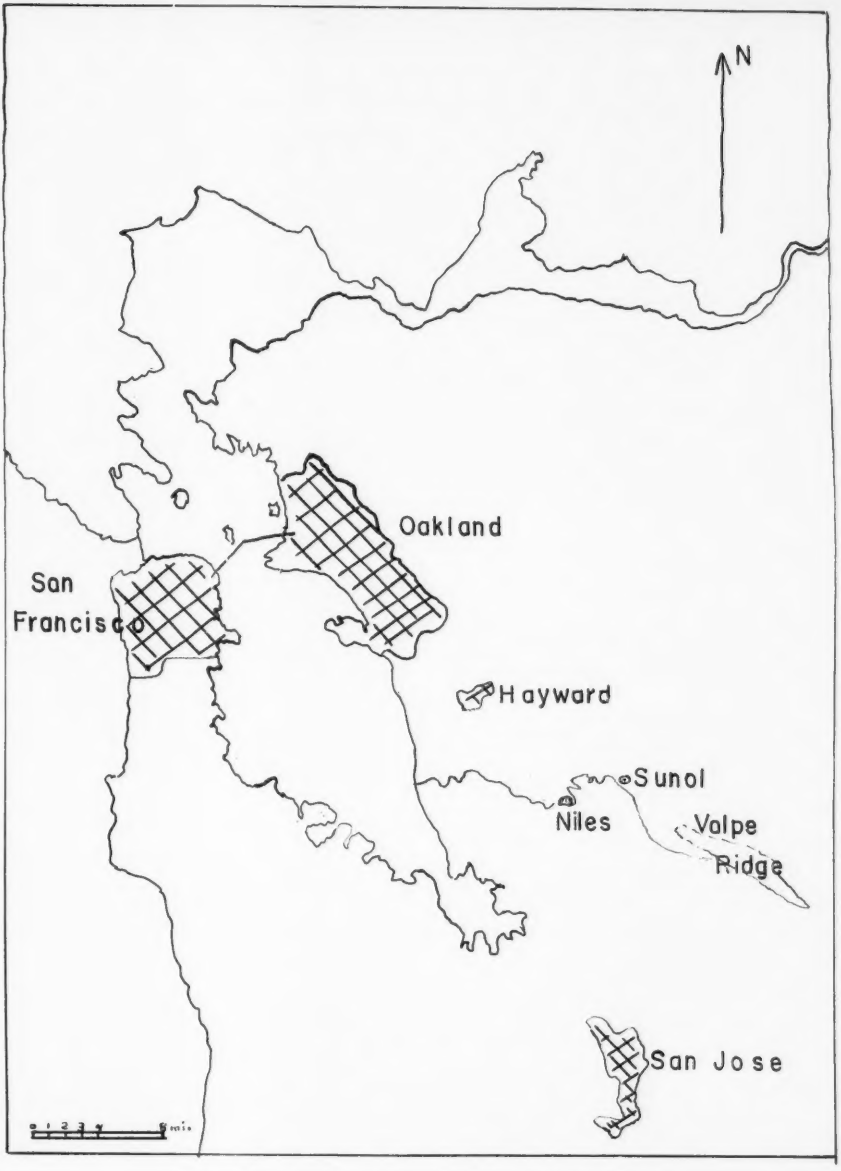

FIG. 1.—Map showing the general location of the area studied.

nantly flows through Jurassic rocks of the Franciscan Formation. These are mainly schist, greywacke, and chert. Sediments in the first half of the course of the creek studied are predominantly chert and schist, but in the last half of the course they are predominantly greywacke.

Alameda Creek is an intermittant stream with water flowing during, and after, long rainy spells. Every few years the stream bed in the Santa Clara Valley is unable to contain the water and a flood results. The rest of the years water flows in only parts of the stream channel.

METHOD OF STUDY

Beginning at the stream's headwaters on Valpe Ridge and continuing 18 miles to the town of Niles, consecutively numbered observation stations were set up at mile intervals. The maximum boulder measurements were taken at every mile station and the size distribution measurements were taken at observation stations 2, 5, 7, and alternate stations thereafter. At each station, the three diameters of all the large boulders, within a distance of 50 feet upstream and 50 feet downstream, were measured with a steel tape. There were usually two to five large boulders in the prescribed area. The intermediate diameter of the largest boulder in the area was used for the graph (fig. 2). Roundness and sphericity of the largest boulder were determined by the use of charts from Rittenhouse (1943) and Krumbein (1941). The petrographic classification of the rock was also recorded. Width of the stream bed at the stations and position of the tributaries were determined in the field and are indicated in figure 2.

At observation stations 2, 5, 7, and alternate stations thereafter, two hundred rocks were measured to determine the size distribution of the gravel. Principles pertaining to size distribution analyses were taken from Wentworth (1926). Throughout the stream bed, the surface layer of gravel was underlain by sand; only the rocks from the surface layer of gravel were measured. The sand particles beneath the gravel layer were considered to represent another population and were not considered in this analysis. The rocks used in the size distribution analysis were measured by placing their intermediate diameter next to a data sheet marked off with columns for each size grade. The data sheet was stiff paper with its top edge marked off in millimeters. A line was drawn from the top scale all the way down the paper at each limiting diameter on the scale. These limiting diameters were 4.00 mm, 5.65 mm, 8.00 mm, 11.30 mm, 16.00 mm, and so on by $\sqrt[3]{2}$ progression. If a rock's intermediate diameter fell into the column between 4.00 mm and 5.65 mm, a mark was put in that column to signify one rock within that particular size grade. After measuring two hundred rocks, the marks in each column were totaled and the volumetric frequency was determined by multiplying the numerical frequency in each size grade column by the cube of the mean diameter of the two limiting diameters of that column; these results are shown in table 2. A separate data sheet was used for each distribution analysis. This method of obtaining field measurements for a distribution analysis was introduced by Emery (1955).

All statistical constants were determined from cumulative curves plotted on the basis of volumetric, or weight, frequencies. Sorting coefficient values and skewness values were determined by the formulas found in Pettijohn (1957, p. 26) which are:

$$\text{Sorting Coefficient} = \sqrt[3]{Q_{25}/Q_{75}}$$

$$\text{Skewness} = \frac{Q_{25} \times Q_{75}}{(M_d)^2}$$

RESULTS AND CONCLUSIONS

Petrographic classification and measurements made on the large boulders are shown in table 1. The intermediate diameter of the maximum boulder and its roundness and sphericity, as shown in table 1, are plotted in figure 2. Also plotted in figure 2 are the stream gradient, width variations of the stream channel, and the median diameter of the gravel.

It can be seen from figure 2 that the maximum boulder size fluctuates throughout the entire length of the stream, but generally decreases as the distance from the headwaters increases. Fluctuations of the maximum boulder size are due to a combination of factors consisting predominantly of changes in the stream gradient and constric-

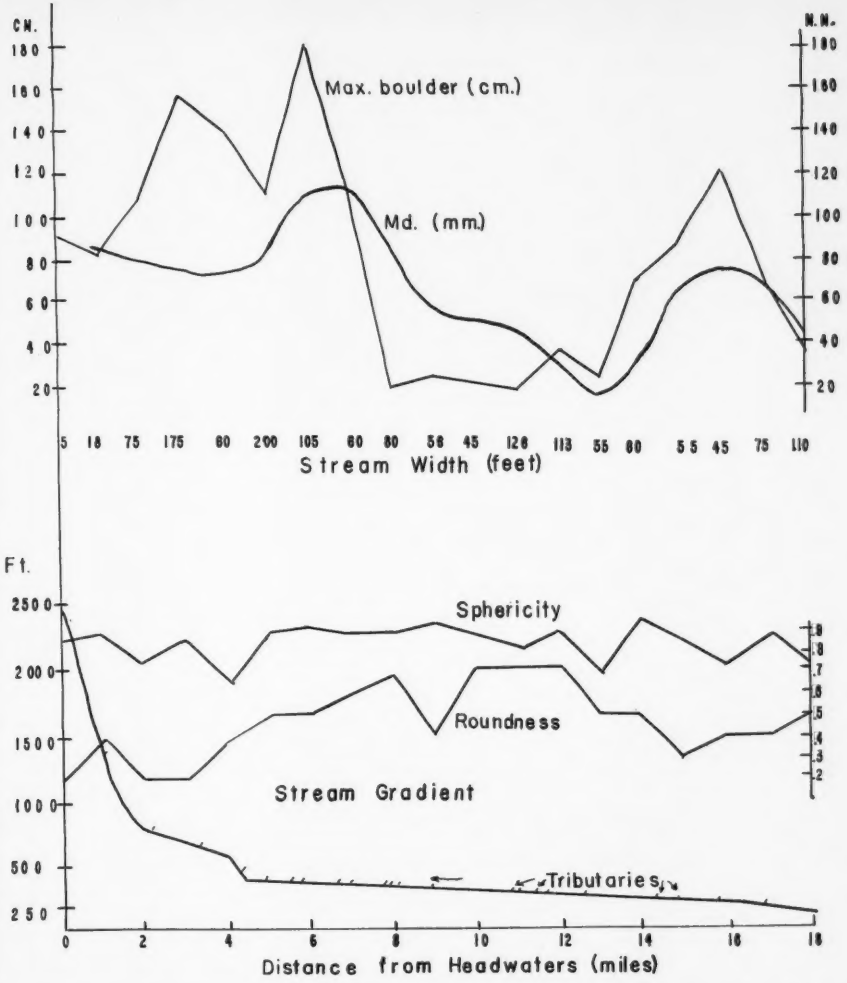

FIG. 2.—Curves on graphs show how the maximum boulder's intermediate diameter, the median diameter of the gravel, roundness and sphericity of the maximum-sized boulders, stream channel width, and stream gradient vary with increasing distance from the stream's headwaters.

tions in the width of the stream channel. Minor factors contributing to the fluctuations are the alluvial cones formed at the mouths of some of the tributaries and the introduction of larger sized sediments into the trunk stream by tributaries.

In their studies relating to river channels, Leopold and Wolman (1952) found that aggradation can, and often does, take place in an area of even and constant slope. This same phenomenon was found in Alameda Creek. Several areas of aggradation, such as

TABLE 1.—*Measurements taken at every mile station*

Station No.	Max. boulder sizes in cm	Largest intermediate diameter used in figure 1	Roundness & sphericity of max. boulder used for the graph		Type of rock
			Roundness	Sphericity	
0	106×99×81 101×92×74 36×25×22	99	.2	.85	Greywacke
1	92×81×74 84×71×63	81	.4	.90	Shale
2	178×109×102 178×89×51 203×99×71 104×76×51	109	.2	.77	Glaucophane Schist
3	24×157×127 142×102×58 74×58×36 130×114×66	157	.2	.87	Greywacke
4	23×140×102 216×127×94 210×127×86 178×107×89	140	.4	.65	Chert
5	137×112×71 109×104×43 147×74×41 99×64×58	112	.5	.89	Peridotite
6	199×175×76 155×69×61 84×48×43	175	.5	.91	Greenstone
7	130×114×97 102×97×43 114×97×69 130×74×61	114	.6	.89	Arkosic Wacke
8	25×20×18 28×18×15 28×20×15	20	.7	.89	Siltstone
9	28×23×18 46×23×15 46×20×15 28×18×13	23	.4	.93	Quartzite
10	25×20×18 23×15×13 25×15×10	20	.7	.89	Arkosic Wacke
11	25×18×13 28×18×13 28×13×8	18	.7	.81	Greywacke
12	48×38×23 41×23×20 28×23×18	38	.7	.89	Arkosic Wacke

TABLE 1.—(*Continued*)

Station No.	Max. boulder sizes in cm	Largest intermediate diameter used in figure 1	Roundness & sphericity of max. boulder used for the graph		Type of rock
			Roundness	Sphericity	
13	30×23×15 13×8×5 15×10×8	23	.5	.72	Diorite
14	79×71×69 74×66×53	71	.5	.93	Arkosic Wacke
15	117×86×84 107×59×53 97×61×56 102×76×61	86	.3	.85	Arkosic Wacke
16	202×119×71 168×102×89 180×115×107 89×66×26 94×69×61	119	.4	.73	Arkosic Wacke
17	137×71×59 97×61×33 145×125×61	71	.4	.86	Quartz Arenite
18	51×33×15 33×31×28 48×25×12 33×23×20	33	.5	.74	Arkosic Wacke

from the two-mile station to the three-mile station, and the thirteen-mile station to the sixteen-mile station, are situated where the stream gradient is fairly constant. (See fig. 2.)

Constrictions formed by the narrowing of the stream channel seem to be partly responsible for the fluctuations in the graphical representation of the maximum-sized boulder. Most noticeable of these is the sharp decrease in the diameter at station eight. The stream channel is 105 feet wide at station six and narrows to 60 feet at station seven; it then widens to 80 feet at station eight. This constriction at station seven has probably formed a hydraulic jump between stations six and seven and caused an increase in the stream's velocity and competence by station seven. The increase in velocity and competence is continued through station eight. Constrictions in stream width caused by alluvial cones at the mouths of the tributaries are very minor and do not cause any fluctuation on the graph of maximum boulder size.

Results of the gravel counts are shown in table 2 and the statistical constants derived from these data are shown in table 3. Median diameter values were calculated from cumulative percentage curves and then plotted on figure 2. The median diameter curve is similar to the maximum boulder size curve. Both curves reach a maximum size value at, or near, the point representing station six and both curves decrease past this point but the maximum boulder size curve reaches its minimum value sooner than the median diameter curve.

Sorting coefficients calculated from the cumulative percentage graphs are also shown in table 3. The average sorting coefficient is 1.38. According to Trask (1932), a perfectly sorted sediment has a coefficient of 1.0 and a value under 2.5 indicates a well sorted sediment. Pettijohn states that the value of 2.5 is too high. He states that

TABLE 2.—*Size distribution of the gravel*

Limiting diam.		Mean diam. (mm)	Vol. $d^3(cm^3)$	Sta. 2			Sta. 5			Sta. 7			Sta. 9		
ϕ	mm			f	%	Cum.%	f	%	Cum.%	f	%	Cum.%	f	—	Cum.%
−2.0	004.00	004.76	0000.108	0000.108	—	—	0000.216	—	—	0000.108	—	—	0000.0	00.00	000.00
−2.5	005.65	006.72	0000.305	0000.305	—	—	0000.610	—	—	0000.610	—	—	0000.3	—	—
−3.0	008.00	009.52	0000.863	0024.100	00.15	000.15	0014.700	00.19	000.19	0017.250	00.07	000.07	0018.1	00.14	000.14
−3.5	011.30	013.50	0002.470	0069.100	00.44	000.59	0042.000	00.42	000.61	0045.300	00.02	000.09	0051.8	00.39	000.53
−4.0	016.00	019.00	0006.850	0356.000	02.28	002.87	0370.000	03.17	003.78	0318.000	01.21	001.30	0390.0	02.78	003.31
−4.5	022.60	027.00	0019.700	0709.000	04.53	007.40	0925.000	07.92	011.70	0865.000	03.28	004.58	0808.0	06.08	009.39
−5.0	032.00	038.00	0054.900	1759.000	11.30	018.70	1868.000	16.00	027.70	2030.000	07.71	012.29	1480.0	11.11	020.50
−5.5	045.10	054.00	0158.000	1900.000	12.20	030.90	2850.000	24.40	053.10	3000.000	11.40	023.69	4110.0	30.95	051.45
−6.0	064.00	076.00	0440.000	2200.000	14.00	044.90	3080.000	27.10	080.20	2220.000	08.38	032.07	2640.0	19.85	071.30
−6.5	090.00	108.00	1270.000	5080.000	32.60	077.50	2540.000	19.80	100.00	1270.000	04.83	036.90	3818.0	2870.	100.00
−7.0	128.00	152.00	3510.000	3510.000	22.50	100.00	0000.000	00.00		17550.000	63.10	100.00	0000.0	00.00	000.00
−7.5	182.00														

Limiting diam.		Mean diam. (mm)	Vol. $d^3(cm^3)$	Sta. 11			Sta. 13			Sta. 15			Sta. 17		
ϕ	mm			f	%	Cum. %	f	%	Cum. %	f	%	Cum. %	f	%	Cum. %
−2.0	004.00	004.76	0000.108	0000.22	—	—	001.51	00.15	000.15	0000.11	—		0000.97	00.01	000.01
−2.5	005.65	006.72	0000.305	0000.61	—	—	004.28	00.41	000.56	0000.31	—		0002.74	00.03	000.04
−3.0	008.00	009.52	0000.863	0031.10	00.39	000.39	042.30	04.08	004.64	0008.63	00.09	000.09	0026.80	00.29	000.33
−3.5	011.30	013.50	0002.470	0089.00	01.10	001.49	123.00	11.90	016.54	0024.70	00.26	000.35	0076.50	00.83	001.16
−4.0	016.00	019.00	0006.850	0342.00	04.31	005.80	342.00	32.20	049.74	0438.00	02.81	003.16	0240.00	02.61	003.77
−4.5	022.60	027.00	0019.700	0631.00	07.90	013.70	355.00	34.30	084.04	0975.00	06.42	009.58	0887.00	09.54	013.31
−5.0	032.00	038.00	0054.900	1210.00	15.10	028.80	165.00	15.96	100.00	1318.00	08.69	018.27	0769.00	08.35	021.66
−5.5	045.10	054.00	0158.000	2210.00	27.70	056.50	000.00	00.00		1265.00	08.33	026.60	0633.00	06.84	028.50
−6.0	064.00	076.00	0440.000	2200.00	27.60	084.10	000.00	00.00		3520.00	23.20	049.80	1760.00	19.20	047.70
−6.5	090.00	108.00	1270.000	1270.00	15.90	100.00	000.00	00.00		9630.00	50.20	100.00	5080.00	52.30	100.00
−7.0	128.00	152.00	3510.000	0000.00	00.00	000.00	000.00	00.00		0000.00	00.00		0000.00	00.00	
−7.5	182.00														

Hough and Stetson have pointed out "that most near-shore marine sediments of the sand grade have sorting coefficients between 1.0 and 2.0. Stetson gives 1.45 as the average" (Pettijohn, 1957, p. 37). It is believed that the range of limits that denote a well-sorted sediment will change as the conditions, or environment, of deposition change. A sorting coefficient that denotes a well-sorted marine sediment does not necessarily also denote a well-sorted alluvial deposit. In the case of recent stream deposits, the value of 1.38 appears to denote a very well-sorted gravel deposit.

Table 3 shows that as the values for the median decrease most of the skewness values increase, indicating skewness towards the smaller classes, whereas the sorting coefficients remain fairly constant. In his work on the flood deposits of Arroyo Seco, Krumbein found that skewness is a function of size and moves toward the smaller size classes as the mean size decreases with distance; whereas, the sorting coefficient shows no systematic change with distance of transport (Krumbein, 1949). This statement is also true for Alameda Creek.

Figure 2 shows that the roundness fluctuates but tends to increase with increasing distance from the headwaters. Superimposed on this behavior is the fact that the roundness increases as the maximum boulder size decreases. The sphericity fluctuates fairly consistently between .72 and .92. These graphs, plus the increasing roundness with decreasing size, support Krumbein's conclusions that the roundness is a function of wear on the pebble over the distance traveled but the size and shape of the pebble are functions of the dynamic conditions at the immediate site of deposition (Krumbein, 1949.)

FIG. 3.—Graph of average sphericity value for each given roundness value.

Figure 3, a graph of average sphericity value for each given roundness value, shows an increase in sphericity with an increase in roundness. This graph is based only on average sphericity figures and it can be seen from figure two that this relationship does not occur in every case. This graph agrees with the findings of Russell and Taylor (1937) in their work on the Mississippi River sands, that sedimentary particles of high sphericity are rounder than those of low sphericity.

Data on recent sediments in Alameda Creek support observations made on other streams concerning stream transport and its various factors. Conclusions concerning the sediments of Alameda Creek within the area studied are as follows:

1. Maximum boulder size and median gravel size decrease downstream.
5. The sediments appear to be well sorted.
3. Skewness is a function of the mean size.
4. Sphericity fluctuates fairly consistently and generally does not tend to increase or decrease.

TABLE 3.—*Statistical constants (mm)*

Sample No.	Median (Md)	Coefficient of sorting (So)	Coefficient of skewness (Sk)	1st quartile (Q_1)	3rd quartile (Q_3)
2	82	1.46	0.70	47	101
5	53	1.38	0.99	38	73
7	115	1.50	0.55	57	128
9	54	1.39	1.12	41	80
11	49	1.37	0.96	35	66
13	19	1.22	1.06	16	24
15	67	1.32	0.97	50	87
17	78	1.43	0.62	46	95

5. Roundness increases with distance downstream.
6. Roundness increases as the size of the rock decreases.
7. Average sphericity figures tend to increase as roundness increases.

It is believed that the decrease in particle size downstream is due to increased abrasion and lessened competence of the stream resulting from a decrease in gradient.

ACKNOWLEDGEMENTS

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FIGS. 1–6, JUNE, 1959

THE IMPORTANCE OF MODES IN CROSS-BEDDING DATA[1]

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ABSTRACT

Cross-bedding data are presented from three sharply restricted channel sandstones, in Oklahoma and Tennessee; from a Pleistocene deposit in Florida; and from the Pottsville sandstones of parts of Kentucky, Tennessee, Georgia and Alabama. Modal vectors are shown to be more useful, in certain instances, for paleogeographic purposes, than vector sums. Pottsville cross-bedding data appear to be essentially tri-modal, with the three modes at right angles to each other. The "minimum direction" is approximately the direction toward the Appalachian sourceland. Asymmetry of the data indicate that littoral currents flowed more readily toward the south than toward the north. A measure of dispersion (n/R) for modal vectors is used to produce a crude map of Pottsville regional slope in northeastern Alabama.

INTRODUCTION

Operational procedures, for manipulating vector data, have been described in several papers (Greenwood and Durand, 1955; Pincus, 1953; Chayes, 1954; Lowell, 1955; Tanner, 1955; Curray, 1956; Pincus, 1956; Potter and Siever, 1956; Niehoff, 1958; Wurster, 1958). Some of these papers also discuss interpretation.

The present note contains directional data for three channel sands (the Doe Creek and Verden sandstones of Oklahoma, and the Pulaski channel filling of Tennessee); a Pleistocene shoreline deposit (the Miami calcarenite of Florida); and Pottsville sandstones of the Southern Appalachian mountains. The measurements have been obtained over a period of about five years, in conjunction with a variety of other field projects. The data are handled as suggested in a previous paper (Tanner, 1955). Greater use is made of vector sums, however, and particularly of modal vectors.

Modal vectors may be obtained by combining all of the field measurements which make up a single mode on a rose diagram or compass diagram. They are superior to vector sums, in many instances, because they permit the separation of significant components. For example, vector data from an estuary might give an easterly direction, whereas sands in a nearby beach or marine bar might yield a southerly direction. A vector sum of the two is not nearly as interesting as the individual directions. Examples of the polymodal nature of cross-bedding data are given in previous papers (Tanner, 1955; Tanner, 1956).

Separation of modes is, in many cases, possible by refiguring class populations to percentages, and plotting on arithmetic probability paper (Tanner, 1958). The details of calculation of vectors are given by Greenwood and Durand (1955). The last-named reference also provides instructions for developing n/R, an important measure of scatter, or dispersion. For this parameter, n is the number of measurements, and R is the length of the vector sum. The inverted form (rather than R/n) is used so that limited scatter will be represented by small numbers, slightly above but close to unity, rather than large numbers. This will be shown below.

It should be re-emphasized here that the use of modes and vectors is based on an important facet of orientation data: circular statistics cannot be handled by the ordinary methods which are quite adequate for linear data. This fact has been made clear in several of the papers cited in the first paragraph.

MIAMI FORMATION

The Miami oölite exhibits clear cross-bedding in wave-cut cliffs and canal walls in the vicinity of Miami, Florida. The formation is Pleistocene in age. There is no doubt that the shoreline, during Miami time, was essentially parallel with the present shoreline in the same area (MacNeil, 1949). The data for Miami cross-

[1] Manuscript received December 12, 1958.

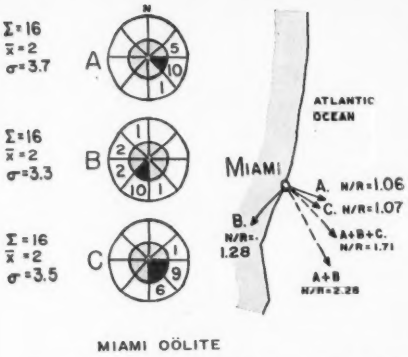

FIG. 1.—Cross-bedding data from three localities in the Miami oölite, near Miami, Florida, shown on compass diagrams and as vectors. Vector sums of total data ($A+B$; $A+B+C$) do not match the geography nearly as well as modal vectors (A; B; C). Numbers given by each compass represent sample total, mean, and standard deviation.

bedding are given in figure 1. Whether vectors or modes are determined, there are two primary directions, one of which parallels the shore, and one of which is at right angles to it.

It is clear that two modes only do not permit an interpretation as to which is which. Littoral transportation along the lower east coast of Florida is dominantly southward today. The same was probably true in the Pleistocene; not a single measurement was obtained in the arc, zero-to-45 degrees.

It is also obvious that modal analysis is superior to vectors which are derived from the entire population (i.e., $A+B$, or $A+B+C$, in fig. 1).

VERDEN SANDSTONE

The Verden Sandstone is restricted to a long, narrow channel crossing the northern side of the Anadarko Basin of Oklahoma (Evans, 1949). It is Permian in age. Figure 2 shows the field measurements obtained. There can be no question about the direction of transport. The shoreline at that time, obtained from other data, was roughly at right angles to the channel. The cross-bedding, as represented by the arrow (i.e., vector) in the figure, doses not duplicate precisely the channel direction.

DOE CREEK SANDSTONE

The Doe Creek, like the Verden, occurs as a long, narrow sandstone member in western Oklahoma (fig. 2). It crosses the present strike of Permian rocks exposed in the same area, and therefore it may have been thought that it crosses the shoreline as does the Verden. The picture for the Doe Creek is, however, not nearly so clear. Much

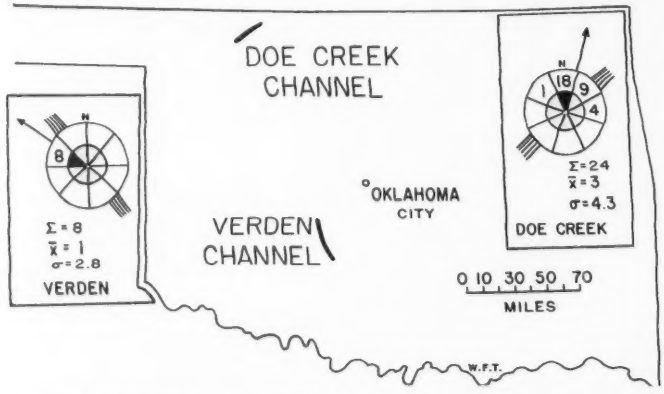

FIG. 2.—Cross-bedding data for the Verden and Doe Creek channel sandstones of western Oklahoma. On each compass is shown the vector sum (arrow) and the channel trend. In neither case do modes or vectors agree precisely with channel trend.

evidence (Tanner, 1954; Raasch, 1946) indicates that the trend of the Doe Creek may have ben nearly parallel with the shoreline. The direction of transport is quite clear; this is a direction away from the present Anadarko Basin. The direction obtained by vector summation (arrow, in figure 2) is 30 or 35 degrees off of the trend, and more nearly at right angles with the inferred Permian shoreline of the area.

PULASKI CHANNEL

The Pulaski channel (fig. 3), of Ordovician age, is located in south central Tennessee. It has been described in detail by Wilson (1948). Field measurements made by the present author are also shown in figure 3. There is a suggestion, in the original data, of two modes, which can be separated by recomputing the class populations to percentages and plotting on probability paper. Simple modal analysis, however, and vector summation reveal a single important direction of transport, not far from the direction taken by the channel.

Wilson discusses reason for thinking that the channel was cut at one time, probably by a river, and filled at a later date, possibly by sea-floor sand. Submarine transportation may account for the faint bimodality.

The mode (and the vector sum, to a lesser degree) deviates from the channel trend. This is perhaps due to the fact that at the sample locality, the channel bends so that it is convex to the south. If the filling were of marine origin, however, there is no need to require that the cross-bedding match a river-flow pattern.

POTTSVILLE SANDSTONES

The Pottsville Group is composed of sandstones and shales of early Pennsylvanian age. Outcrops in Alabama, Georgia, Tennessee and Kentucky were studied (fig. 3, shaded areas). Six localities in the Tennessee-Kentucky area yielded relatively large numbers of measurements: near Middlesboro, Kentucky (32 measurements), near Morely, Tennessee (24), and near LaFollette, Tennessee (24). In addition, eight localities were sampled in extreme northwestern Georgia, and 17 localities in northeastern and central Alabama. The

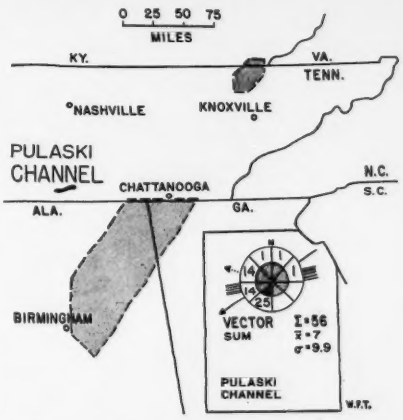

FIG. 3.—Map of parts of seven southeastern states, showing the location of the Pulaski channel in Tennessee and areas from which Pottsville cross-bedding data were obtained. The inset shows, for Pulaski data, the vector sum (solid arrow), a modal vector for a faint secondary mode (dotted arrow), and the channel trend.

locations of the 25 localities in Georgia and Alabama are given in figure 4, along with a summary of the modal analyses.

Vector sums representing the significant modes are presented in figure 5. Vector sums calculated, without recourse to modal analysis, were not used, for reasons illustrated by the Miami calcarenite data (fig. 1).

The northern area (Kentucky and Tennessee) differs considerably from the southern. The summary of individual measurements (compass, fig. 5) shows a single preferred direction (south-south-west octant) and a secondary mode of doubtful significance (east-south-east octant). From this compass, however, no clear-cut conclusions can be drawn, other than the chief direction of transport. Individual compasses from the sample localities are much clearer, but the diagram of modal vectors (fig. 5) is clearer still.

The southern area (Alabama and Georgia) contains two patterns, *A* and *B*, which can be seen on the compasses (fig. 4) or the modal vector diagrams (fig. 5). If these two sets of data are combined, without weighting, two significant modes appear: west-north-west and south-south-west. Since

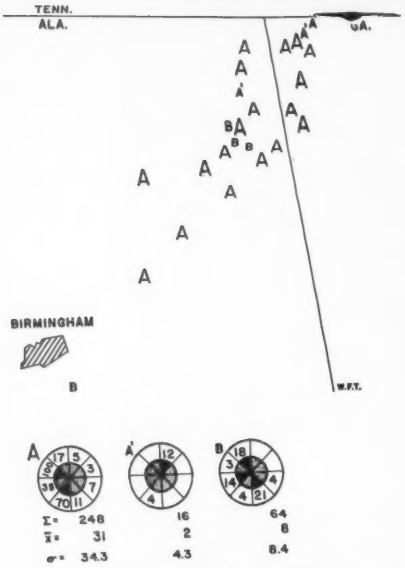

FIG. 4.—Pottsville cross-bedding measurements in Alabama and Georgia yielded three typical patterns, of which *A* is by far the most common. The locations of compasses of these types are shown by the capital letters on the map. For example, the *B* pattern southeast of Birmingham is tri-modal, just like the total *B* pattern shown.

they are at right angles, a shoreline interpretation, such as that made in figure 1, is suggested, but no firm conclusion can be drawn as to the orientation of the shoreline. If these two sets of data are combined, with *B* given the same weight as *A*, only a single octant is significantly high: west-north-west. In both combinations, the northeast quadrant is significantly low.

Calculation of modes, and modal vectors, at each sample locality, yields compass patterns identical (or nearly so) with those in figure 4, and the vectors in figure 5. The *A'* component is separated for convenience, since it offers a reasonable complement to *A*.

A pattern of down-slope and littoral transportation emerges, with the shoreline oriented north-north-east, south-south-west, and the source-land to the east. Further, since the northeast octants are low, the net littoral motion may have been toward the south.

The *B* pattern provides a complication. It is possible that the shoreline was indented or crenulate; or the sand represented by *B* may have been deposited during a temporal or spatial change in shore-line orientation, or by currents which did not move directly down slope.

The modal vectors which represent the two patterns (*A* and *B*) possess length as well as direction. The length may be expressed as n/R, following Greenwood and Durand (1955). This value has been plotted, for each sample site where a west-north-west mode was obtained, in figure 6. The values so plotted (shown as arrows, northeast of Birmingham) have been used as the basis

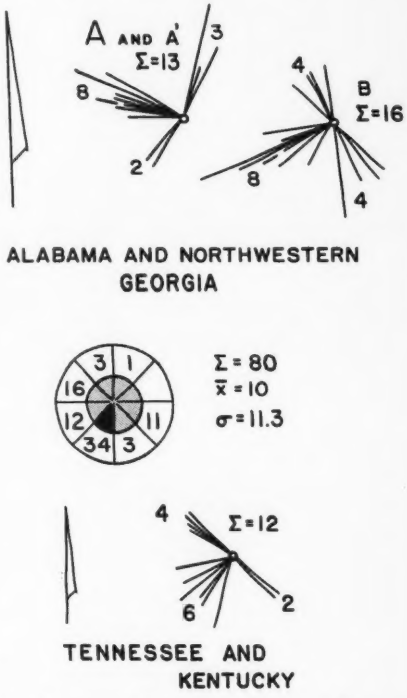

FIG. 5.—Modal vectors for Pottsville cross-bedding, for all areas worked, and compass data for the Tennessee-Kentucky area. Each line is a vector, with length equal to n/R, representing a significant mode and its adjacent measurements.

for a system of isopleths, or form lines, which parallel modal vectors obtained from the south-south-west and north-north-east octants.

The value, n/R, is a measure of the concentration of directions. Low numerical values, approaching unity as a lower limit, indicate a very narrow arc over which the directions are spread; high values, such as 2.0, indicate a much wider arc (that is, much more scatter). This parameter, therefore, serves for circular data in much the same way as the variance or standard deviation does for linear computations. Table 1 lists approximate values for n/R interpreted in terms of degrees of arc, based on the assumption that the measurements involved are uniformly distributed within the arc given.

The value, n/R, measures the consistency with which the transporting agency maintained a single direction, with unity indicating very high consistency. For this reason, n/R approximates the slope of the energy gradient over which the sand were moved. The important components in this gradient are bottom slope, current direction, and wave direction. For modal vectors which lie at right angles to the inferred littoral drift, the most important component is slope. The value, n/R, is, therefore, a rough indicator (for certain modal vectors) of the regional sope.

TABLE 1.—*Approximate values of n/R for various arcs. (The assumption is made that the measurements are uniformly distributed within the arc given.)*

n/R	°arc	n/R	°arc
1	0	1.30	136
1.005	15	1.35	144
1.01	25	1.40	152
1.02	35	1.45	160
1.03	43	1.50	166
1.04	50	1.60	178
1.05	56	1.70	188
1.06	62	1.80	206
1.07	68	1.90	211
1.08	73	2.00	215
1.09	78	2.5	240
1.10	84	3.0	265
1.15	100	3.5	280
1.20	115	∞	360
1.25	126		

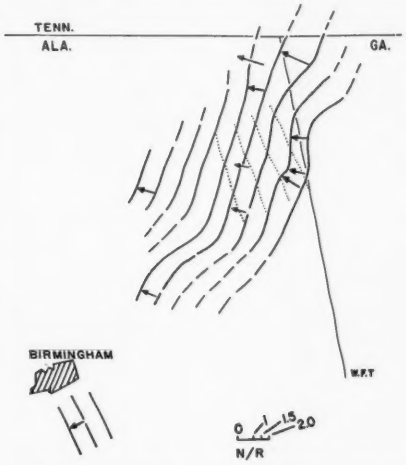

FIG. 6.—Isopleth map of the value, n/R, for selected modal vectors in the Georgia-Alabama area. Solid lines northeast of Birmingham represent pattern *A*; dotted lines northeast and solid lines southeast of Birmingham, pattern *B*.

Figure 6 shows what is inferred to be such a slope. The isopleths are, at all points, spaced according to n/R, and drawn parallel to littoral-drift vectors. They can be interpreted in terms of direction of slope, and relative amount of slope, with the reservation that wave and current deviations, although probably not great, are nevertheless not known.

The *A* pattern in figure 6 (solid lines northeast of Birmingham) is, roughly, what one would expect from the known paleogeography. The *B* pattern (dotted lines northeast of Birmingham, and solid lines southeast of Birmingham) may represent:

1. Irregularities in the shoreline.
2. Temporary changes in shoreline orientation.
3. Spatial changes in shoreline orientation.
4. Deposition by currents which did *not* flow directly down slope.

Because the *A* pattern is, numerically, so much more common than the *B* pattern, it is thought that the *A* orientation yields the best approximation to the average shoreline orientation of early Lee time.

A preliminary study of the Pottsville

sandstone data, using vector sums rather than modal vectors, had the effect of combining patterns *A* and *B*, thus yielding north-south isopleths. The present analysis, using modal vectors, appears to be more satisfactory. It is important that error of this type (masking modal patterns by use of a measure of central tendency) be recognized and avoided (Niehoff, 1958; Wurster, 1958).

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FIG. 1, JUNE, 1959

FELDSPAR STAINING METHODS[1]

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ABSTRACT

A feldspar staining technique, based upon the method described by Gabriel and Cox, was tested for accuracy and reliability by using both artificial mixtures of quartz and feldspar, and natural sands. The sand grains are mounted on a glass slide, exposed to the fumes of hydrofluoric acid for 15 minutes, treated with a concentrated solution of sodium cobaltinitrite for 2 minutes, rinsed, and dried. This reaction forms a yellow coating on the potash feldspars, a white coating on the soda-lime feldspars. and the quartz is not affected. For greater accuracy, the sample may then be treated for a few minutes with a 0.5 percent solution of eosine "B." This will stain the soda-lime feldspars pink and the potash feldspars orange-yellow.

Tests on 70 slides of artificial mixtures of quartz and feldspar show that the method is accurate to plus or minus 5 percent. Percentages determined by multiple tests on natural sands show good agreement, usually to within 5 percent.

INTRODUCTION

The determination of the quartz-feldspar ratio of clastic sediments by ordinary optical methods is a lengthy, tedious process which tends to discourage the study of a large volume of samples. Too often this ratio is estimated on the basis of a cursory examination under a binocular microscope or hand lens.

Staining is a rapid and reliable method for distinguishing quartz from feldspar. Gabriel and Cox (1929) describe a method whereby the disaggregated sample is exposed to the fumes of hydrofluoric acid, treated with a concentrated solution of sodium cobaltinitrite, rinsed, and dried. This reaction forms a yellow coating of potassium cobaltinitrite on the potash feldspars, and a white coating on the soda-lime feldspars. Quartz is not affected. To more readily identify the soda-lime feldspars, the sample may be treated with eosine "*B*," a water-soluble organic dye. The white coating on the soda-lime feldspars absorbs the dye and becomes pink, the potash feldspars change from yellow to orange-yellow, and the quartz remains clear. To expose the sample to the fumes of hydrofluoric acid, Gabriel and Cox used a rather cumbersome lead box. No indication of the probable accuracy or reliability of the method was given.

Russell (1935) used two slides in his method; one to determine, by staining, the percentage of quartz and total feldspar, and the other to subdivide the feldspars by optical methods. In his staining technique, he mounted a representative sample on a glass slide so that the upper surfaces of the grains were exposed, applied hydrofluoric acid directly to the grains for about one minute, and then carefully rinsed the slide. The grains were then treated for about five minutes with a water-soluble organic dye, such as malachite green, and again gently rinsed. The feldspars absorbed the dye whereas the quartz was unaffected. Russell stated that the reproducibility of the method was within 3 percent. Many of the well-known texts of sedimentary petrography suggest this method. (Krumbein and Pettijohn 1938, p. 495–496; Twenhofel and Tyler 1941, p. 131; and Pettijohn 1957, p. 124.)

Willman (1942) in his studies of the feldspar content of sands in Illinois used a variation of Gabriel and Cox's method. He applied the acid directly to the grains, as suggested by Russell. Chayes (1952) outlined an application of Gabriel and Cox's method of the study of thin-sections and recommended the use of a plastic or polyethylene fume box.

A recent application of Russell's method in a petrographic study of some Paleozoic formations of central Colorado showed poor reproducibility. A check of the procedure showed that the final rinsing after the

[1] Manuscript received December 22, 1958.

treatment with malachite green was the critical point. If the slides were rinsed sufficiently to remove the dye from the quartz, much of the dye was also removed from the feldspar. As a check, eight graduate students, using Russell's method, tested samples collected from three formations. For the Cretaceous Fox Hills Sandstone the quartz percentages varied from 20 to 88 percent, for a sandstone in the Pennsylvanian Maroon Formation it varied from 41 to 94 percent, and in the Jurassic Garo Sandstone it varied from 83 to 100 percent.

Considerable time was spent by the writers in an attempt to improve Russell's method. Exposure times to hydrofluoric acid and dyes were varied, different organic dyes were used, and various methods of rinsing tried. No combinations that were tried gave consistent results. Continued testing indicated that consistent results were obtained by using the basic principles given by Gabriel and Cox (1929). The yellow coating on the potash feldspars and the white coating on the soda-lime feldspars are quite stable and relatively insensitive to rinsing.

STAINING PROCEDURE

A suggested staining procedure, based on the method of Gabriel and Cox (1929) follows:

Sample preparation: The sample is disaggregated. If the grains are coated with iron oxide, they are cleaned in an ultrasonic cleaner or with hydrochloric acid and stannous chloride. A mechanical analysis is made, and one or more size fractions selected for staining. Heavy minerals are removed and the "light" fraction is washed with alcohol and dried. Using a micro-split, a sample of about 500 to 1000 grains is split out of the "light" fraction. A glass slide is heated, lightly coated with Lakeside #70, and excess cement is scraped off with a knife blade. The grains are sprinkled evenly on the slide, and the slide is allowed to cool. One of the most common errors in mounting is the use of too much cement. The upper surface of the grains should project above the cement. If too much cement is used the grains will be covered, thus preventing the reagents from acting on the grains. Another method of mounting the grains is given by Russell (1935). After the slide has been given a thin coating of cement, it is allowed to cool until the cement hardens. The grains are sprinkled on the cement, the slide warmed to permit the grains to sink in slightly, then allowed to cool.

Staining: A plastic or polyethylene box is used to expose the grains to the hydrofluoric acid. The box, equipped with a tightly fitting cover, should be provided with plastic bars to hold the slides about $\frac{1}{2}$ inch above the acid in the bottom of the box. In the present experiments a sandwich box, about 4 inches square and 1 inch deep, purchased at the local variety store, accommodated 4 slides. Plastic soap boxes or covered butter dishes could also be used. A grill, in this case an open plastic soap stand, is placed in the box above the level of the acid. The slides are placed on this grill, the cover replaced, and the slides exposed to the fumes for 10 to 15 minutes.

After exposure to the fumes, the slide is removed, placed grain side up in a shallow dish, and a concentrated solution of sodium cobaltinitrite is applied by dropper until the slide is completely covered. After about two minutes, the sodium cobaltinitrite is rinsed under a gently flowing water tap. The slide is then dried under an infra-red lamp and is ready to count. Mixed in small quantities to insure freshness, the concentrated solution of sodium cobaltinitrite is prepared by adding about 5 grams of the powdered sodium cobaltinitrite to 10 ml of warm water and cooled to room temperature. As a precautionary measure, a loosely fitting glass stopper is recommended for the storage bottle, as a build-up of pressure in a tightly stoppered bottle may produce highly colorful but disastrous results on the walls of the laboratory.

Counting: Any type of microscope may be used in counting; the authors prefer a petrographic microscope equipped with a mechanical stage and with provision for both reflected and transmitted light. A count is made of 300 to 500 grains, separating the grains into three groups—quartz, potash feldspar, and soda-lime feldspar. The potash feldspars will have a yellow coating, the soda-lime feldspars will have a white powdery coating, and the quartz will be

TABLE 1.—*Artificial mixtures, percent by weight*

Mixture	Quartz	Potash Feldspars			Soda-lime Feldspars				
		Micro-cline	Ortho-clase	Total	Albite	Oligo-clase	Bytown-ite	labrador-ite	Total
1	60	40		40					
2	85	5	5	10	5				5
3	75	10	5	15				10	10
4	0	20	20	40	20	20	20		60
5	50				15	15	10	10	50
6	55	15	5	20	5	10	10		25
7	100								
8	30	40	20	60	10				10
9	15	15	15	30	10	20	15	10	55
10	25	15	35	50	10		15		25

clear. A check of the quartz-total feldspar ratio may be made by treating the slide with 0.5 percent solution of eosine "*B*" for about three minutes, then rinsing and drying. The soda-lime grains will now be pink, the white powder having absorbed the dye; the potash feldspars will be orange-yellow, and the quartz will remain clear. This procedure makes the feldspar grains stand out and aids in counting; but it is not always necessary, expecially after some experience is gained in counting the grains. In particularly fine-grained material, the eosine "*B*" staining greatly facilitates the counting.

TESTS OF METHOD

In order to determine the reliability and accuracy of the method, a series of tests was made on both artificial mixtures and natural sands.

Artificial mixtures: Ten mixtures of variable weight percentages of quartz, potash feldspar, and soda-lime feldspar were prepared (table 1). N. C. Schieltz, Metallurgy Department, Colorado School of mines, later checked the minerals by X-ray diffraction and R. M. Hutchinson, Geology Department, Colorado School of Mines, checked some of the minerals petrographically.

The crushed minerals were passed through screens, and the sizes corresponding to medium and fine-grained sand were used. Seven slides were prepared from each mixture and stained as outlined above. The percentages of quartz, potash feldspar, and soda-lime feldspar determined are given in table 2. In most cases the percentage of quartz was checked by making a second count after staining with eosine "*B*."

Natural sands: To test the procedure on natural sands, samples were collected from the Cretaceous Fox Hills Sandstone, Permian Lyons Sandstone, and Pennsylvanian Fountain arkose. Five slides were prepared from each and percentages were determined. The results are shown in table 3. Campos (1958), in a study of local stream sands,

TABLE 2.—*Stain test results, artificial mixtures*

Mix-ture	Quartz		Potash Feldspar		Soda-Lime Feldspar	
	% by weight in mixture	% by staining	% by weight in mixture	% by staining	% by weight in mixture	% by staining
1	60	58, 60, 65, 62, 52, 67, 65	40	23, 31, 30, 31, 24, 22, 26	0	19, 9, 5, 7, 24, 11, 9
2	85	88, 73, 85, 79, 79, 75, 85	10	10, 14, 7, 11, 12, 11, 6	5	2, 13, 8, 10, 9, 14, 9
3	75	76, 82, 71, 79, 75, 73, 80	15	19, 9, 14, 12, 12, 10, 11	10	5, 9, 15, 9, 13, 17, 9
4	0	3, 4, 0, 0, 0, 0, 3	40	40, 36, 34, 39, 38, 40, 37	60	57, 60, 66, 61, 62, 60, 60
5	50	53, 46, 57, 51, 48, 48, 39	0	0, 0, 5, 5, 0, 0, 22	50	47, 54, 38, 44, 52, 52, 39
6	55	55, 46, 55, 55, 47, 49, 53	20	17, 20, 19, 16, 20, 12, 9	25	28, 34, 26, 29, 33, 39, 38
7	100	100, 100, 100, 100, 98, 100, 100	0	0, 0, 0, 0, 0, 0, 0,	0	0, 0, 0, 0, 2, 0, 0
8	30	34, 29, 33, 36, 38, 36, 35	60	45, 52, 53, 43, 49, 53, 57	10	21, 19, 14, 21, 13, 11, 8
9	15	17, 17, 17, 18, 23, 14, 16	30	24, 29, 41, 42, 23, 28, 23	55	59, 54, 42, 40, 54, 58, 61
10	25	26, 28, 25, 21, 30, 28, 28	50	48, 44, 46, 46, 38, 38, 43	25	26, 28, 29, 33, 32, 34, 29

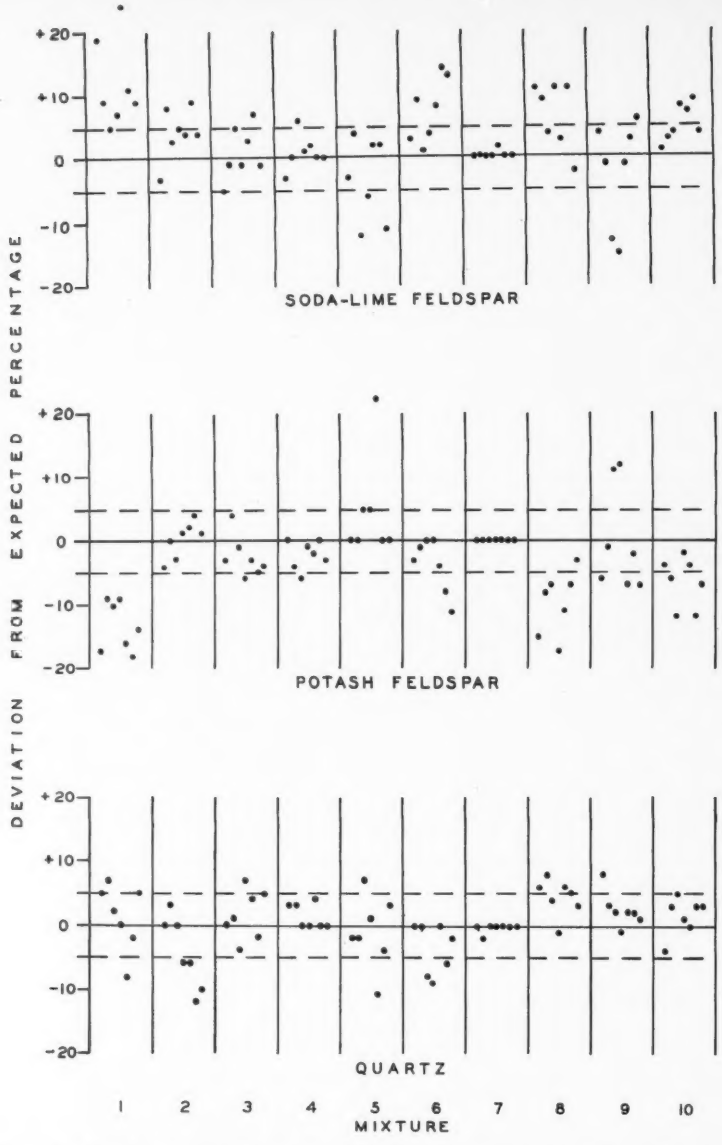

FIG. 1.—Deviation of percentages by staining from the weight percentages in the artificial mixtures. Note that deviations are uniformly distributed in quartz, but that staining tended to give low values for potash feldspars and high values for soda-lime feldspars. This is especially true for mixtures 1 and 8 and is believed due to perthitic nature of microcline used in the mixtures.

TABLE 3.—*Stain test results, natural sands*

Formation	% Quartz	% Potash Feldspar	% Soda-lime Feldspar
Fox Hills (Cretaceous)	51, 50, 49, 50, 47	39, 40, 40, 39, 43	10, 10, 11, 11, 10
Fountain (Pennsylvanian)	44, 42, 42, 41, 47	52, 56, 55, 54, 50	4, 2, 3, 5, 3
Lyons (Permian)	88, 88, 81, 86, 86	9, 7, 13, 9, 8	3, 5, 6, 5, 6

used the procedure to determine the quartz-feldspar ratio. In three instances he prepared a second slide to check his first determinations, which appeared abnormal. In one instance a second sample from 50 feet downstream from the first was collected and analyzed. The results of his check determinations are shown in table 4.

Conclusions drawn from tests: The results of the tests on the artificial mixtures indicate that the staining procedure is simple and efficient. The chart shown in figure 1 expresses the deviations from the expected percentages. In the quartz determinations, 54 of the 70 slides, or 77 percent, gave a deviation of 5 percent or less, only 2 slides deviated more than 10 percent. The average deviation for quartz was 3.2 percent. The potash feldspar determinations show 43 of 70 slides, or 61 percent, with a deviation of 5 percent or less; 13 deviations were greater than 10 percent. The results of the soda-lime determinations are similar to that of the potash feldspars with 43 of 70 slides, or 61 percent, having a deviation of 5 percent or less; and in 12 slides the error was greater than 10 percent. The average deviation was 5.3 percent for the potash feldspars and 5.4 percent for the soda-lime feldspars. In general, the staining results were low for the potash feldspars and high for the soda-lime feldspars. Two of the mixtures, numbers 1 and 8, gave consistently poor results in feldspar determinations. Both mixtures contained 40 percent microcline, and a check of this microcline by R. M. Hutchinson showed it to be perthitic, with an appreciable amount of albite present. If the results of these two mixtures are not considered, the average deviation from the expected percentage of potash feldspar is reduced to 3.7 percent and 4.4 percent for the soda-lime feldspars.

TABLE 4.—*Recent stream sands, stain tests (Carlos Campos, analyst)*

Samples	% Quartz	% Potash Feldspar	% Soda-lime Feldspars
Clear Creek			
Cc 4	39	17	44
Cc 4-A	38	17	45
Bear Creek			
BC 4	41	24	35
BC 4-A	44	19	37
Mount Vernon Creek			
MVc 2	44	17	39
MVc 2-A	42	17	41
MVc 2-B (50′ downstream)	43	14	43

Krumbein and Rasmussen (1941), in a study of the probable errors in heavy mineral analyses, give a laboratory error for splitting, mounting, and counting of 10.5 ± 2.0 percent. The same procedures were used in preparing the slides in this study, and the results indicate that the errors are of the same magnitude that should be expected in the laboratory procedure. The authors believe that the method should give consistent results with an accuracy of plus or minus 5 percent; and that, in general, the quartz-total feldspar ratio should be the most reliable.

In the test conducted on natural sands, the reproducibility is slightly better than in the artificial mixtures. This may be due to a more thorough mixing than that accomplished in the artificial mixtures.

SUMMARY

The staining procedure first described by Gabriel and Cox (1929) is a simple and efficient method for determining quartz-feldspar ratios in sandstones. The procedure is relatively fast, and laboratory procedure is not critical: the coatings formed on the feldspars are stable and not overly sensitive to rinsing. Tests indicate the method is at least as accurate as heavy mineral analyses

and, in general, should give an accuracy of plus or minus 5 percent.

ACKNOWLEDGEMENTS

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FIGS. 1–9, JUNE, 1959

THE PHOTO-EXTINCTION METHOD FOR THE MEASUREMENT OF SILT-SIZED PARTICLES[1]

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ABSTRACT

The photo-extinction method for small particle analysis depends on the absorption of light by silt-size particles in suspension. The rate of change of absorption in a sedimentation cell is related by Stokes' law to the particle diameter. By the use of graphical integration, continuous size distribution curves were constructed for samples of silt, loess, and volcanic ash. In order to compare the photo-extinction method with the more familiar pipette, hydrometer, and microscope methods, samples of the loess were analyzed using the four techniques. Results obtained with the photo-extinction method are reproducible, compare favorably with data obtained by use of the standard microscope method, and are superior to results obtained by either the pipette or hydrometer method.

INTRODUCTION

The study of detrital sediments is based on the analysis of the properties of the particles. One of the most significant of these properties is particle size. Particles larger than $\frac{1}{16}$ mm are generally analyzed with sieves while smaller ones are best measured by some indirect means such as subsidation or elutriation (Twenhofel and Tyler, 1941, p. 46). For many studies the more important sizes are those above the upper limit for the clay-size particles, that is, above 1/256 mm (Twenhofel and Tyler, 1941, p. 63). The range of silt-sized particles therefore constitutes an important part of the particle size analysis, but these particles are in general measured by indirect means which do not necessarily correlate with direct methods.

The history of the older methods of particle size analysis was reviewed by Krumbein (1932a), but since 1933, and expecially during the past ten years, a new method for the determination of silt-sized particles has appeared which offers many distinct advantages. This method, termed the photo-extinction method, was introduced by Wagner (1933) for use in the measurement of silt-sized cement particles. This method offered so many possibilities that considerable research effort was spent upon it in England where it was subsequently developed on a sound mathematical and experimental basis by Rose (in 1953). One of the most attractive features of the photo-extinction technique, is that recording equipment may be utilized with it.

It is proposed to first outline the theory of the photo-extinction method, and then to discuss data gathered using the hydrometer, the pipette, and the photo-extinction methods in comparison with data from direct measurements made with the microscope. It is the purpose of this paper to show that the photo-extinction method offers geologists engaged in measuring the size distribution of silt-sized particles certain distinct advantages over other methods in current use. Therefore, the discussion is limited to silt-sized particles or, more precisely, to those particles whose nominal diameters lie between 2 and 60 microns.

For the sake of brevity the photo-extinction method is referred to as the PE method.

THEORY

General.—In theory, at least, the most direct means of obtaining a particle size distribution is by actually measuring the individual grains under a microscope with the use of a calibrated scale. This method has become the absolute reference standard for checking other methods (Herdan, 1953, p. 436), and in 1933 it was adopted as a tentative test method by the American Society for Testing Materials (1944). How-

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ever, the microscope method has certain disadvantages. Aside from the obvious fact that this method is most time consuming and quite tedious, there are certain intrinsic sources of error that should be considered.

Since only a very small portion of the material is actually measured, it is extremely important to obtain a representative sample. This involves selecting a portion of the material, dispersing it, and then mounting it on a microscope slide. The selection may be made on the basis of random samples if the different sizes of the material are mixed uniformly, or it may be accomplished by use of a microsplitter. The individual particles must then be separated, usually with the aid of some form of dispersing agent. Dispersing agents now in use include xylol and balsam, turpentine, ethanol, sodium silicate, gum arabic (Schweyer and Work, 1941, p. 3), dilute acids, strong alkalies, and such dilute electrolytes as ammonium hydroxide and sodium oxalate (Krumbein and Pettijohn, 1938, p. 56). Obviously, the sample must be adequately dispersed on the slide if representative results are to be obtained. In mounting, it is necessary that the mounting medium have an index of refraction that differs sufficiently from that of the material to insure good optical contrast. Vagueness of the grain boundaries introduces unnecessary uncertainties in the results.

It is important to recognize that the counting technique employed in the microscope method leads to a numerical frequency distribution in contrast to the weight frequency distribution obtained by sedimentation methods. That is, data are obtained which show that for a total of 1000 particles, for example, there are 40 particles which have "diameters" between 2 and 4 microns, 50 between 4 and 6 microns, etc. These quantities reflect the size distribution on a number basis only. The number distribution, however, may be converted to a weight distribution by multiplying the number, N_n, in each class interval by the factor:

$$\frac{D_n d_n^3}{\sum_{n=0}^{N} N_n D_n d_n^3}, \qquad (1)$$

where D_n is the specific gravity and d_n is the mean diameter for the given interval. In practice, the average specific gravity of the various class intervals is assumed constant because the material has previously been subjected to heavy medium separation and the particles thereby essentially separated on the basis of density. In (1) then, the D_n's may be cancelled and the expression becomes

$$\frac{d_n^3}{\sum_{n=0}^{N} N_n d_n^3}. \qquad (2)$$

It is noted that when the weight distribution is the principal requirement of a microscopic analysis, a rather serious condition is imposed. The larger particles contribute far more toward the distribution than the smaller ones. Consider a 2 micron particle and a 50 micron particle with the same specific gravity. The larger particle will weigh 15,625 times as much as the smaller one. Hence the accidental omission of one of the larger particles in counting (a few thousand particles) will lead to a far larger error in the results than the omission of a much larger number of smaller particles. Payne (1948, p. 8), who was interested in the 0–100 micron range, points out that for each 100-micron particle counted, one should be prepared to count a million 1-micron particles. This observation poses a serious restriction on the microscope method for general use.

However, with a standardized technique such as the A.S.T.M. method, the microscope method serves quite well as a reference. It is proposed in this paper to use results obtained by the microscope method as the standard of comparison for the hydrometer, the pipette and the PE methods. It is necessary to adopt some definition of the "diameter" to be used for a given particle. Many concepts of diameter for irregularly shaped particles have been proposed. The one selected for this study is Martin's statistical diameter (Herdan, 1953, p. 66), which is defined as the length of the line which when intercepted by the particle boundaries bisects the projected area of the particle. This line is always taken parallel to some arbitrary fixed direction (in practice, parallel to the scale of the microscope) and is independent of the orientation of the particle (fig. 1). This device effectively re-

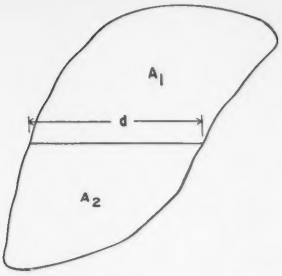

FIG. 1.—Martin's diameter. $A_1 = A_2$.

moves any operator bias in choosing a direction to bisect the particle profile. Martin's diameter is a consistent estimator of the projected area of the particles (See, for example, Chayes, 1956, chapter 1), and if the particles are essentially three-dimensional, the cube of this diameter will then be an estimator of the volume. However, if the particles approach a two-dimensional shape, that is, if they each possess two dimensions which are, in general, much larger than the third, then the short dimension in the most stable equilibrium position will be normal to the microscope stage, and hence Martin's diameter squared will more nearly represent the true volume. This condition existed in one of the materials used for the illustration of the PE method in this work and the size frequency distribution was converted to a weight frequency distribution by the factor

$$\frac{d_n^2}{\sum_{n=0}^{N} N_n d_n^2}. \tag{3}$$

Presumably, the weighting factor for a one-dimensional particle, i.e., one with two dimensions which are each much smaller than the third, should be

$$\frac{d_n}{\sum_{n=0}^{N} N_n d_n}. \tag{4}$$

Many equivalent forms of Stokes' law are found in the literature. The one most useful for direct calculation of diameter is,

$$d_s = \left[\frac{18nh}{(D_s - D_m)gt}\right]^{1/2} \tag{5}$$

where:

d_s = Stokes' diameter,
n = viscosity of the medium,
h = sedimentation height,
D_s = density of the particles,
D_m = density of the medium,
g = acceleration due to gravity, and
t = sedimentation time.

Discussions of the validity of Stokes' law are rather numerous (for example, Krumbein and Pettijohn, 1938, p. 96), but it will suffice here to point out that Stokes' law holds over the 2 to 60 micron range for most particles of geological significance.

The pipette method was introduced by Krumbein in 1932 (Krumbein, 1932b) and subsequently became the working standard for the geological profession in the measurement of fine grained particles. This method possesses the attractive qualities of being mathematically sound, relatively simple, and requiring little in the way of apparatus. On the other hand, it has disadvantages, as follow: (1), considerable experience in the method is required to achieve satisfactory results; (2), a limited resolution of data is obtained; and, (3), the use of automatic continuous recording is precluded.

The hydrometer method as developed by Bouyoucos (1927) for the study of soils also suffers from inherent difficulties. One difficulty is that the hydrometer bulb is fairly large in relation to the desired sampling interval. Ideally, the interval sampled should be infinitesimal, but the hydrometer measures the integrated specific gravity over an interval of a few inches. Another difficulty arises with the insertion of the hydrometer which obviously disturbs the suspension and changes the settling times of the particles. Of course, the hydrometer may remain in the suspension, but the weight of the particles that settle on the hydrometer itself also produces large errors.

Photometric methods.—In contradistinction to the pipette and hydrometer methods which measure the change in density of the system, the photometric methods analyze changes of various properties of a light beam which passes through the system. There are several different phenomena associated with the passage of a parallel beam of light through a polydisperse suspension containing

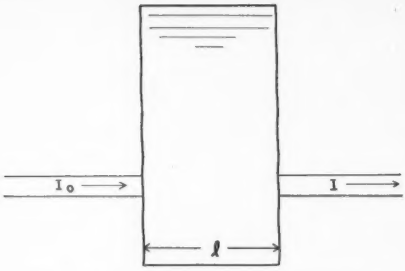

FIG. 2.—The photo-extinction method (schematic).

particles less than 60 microns in diameter. These various effects are measurable and, in conjunction with Stokes' law, form the basis for a general group of methods for determining particle size termed photometric methods. The phenomena include scattering, absorption, and depolarization. Atherton (1952) has used the ratio of the intensity of the scattered light to the intensity of the incident radiation to obtain size distributions in the range below 20 microns. The depolarizing effects of the suspension upon polarized incident light may also be used to obtain a distribution curve (Roller, 1937). A method which depends on the absorption of light is used in the water supply industry to obtain an estimate of the gross amount of suspension irrespective of size distribution (Matheson, 1950 and General Electric Review, 1950). Such gross analyses, however, find little use in the field of geology. The PE method is also based upon the absorption of light but yields information concerning the size distribution. Let us examine this method in more detail.

Photo-extinction method.—Consider the rectangular cylinder shown in figure 2. Let it be filled with a mixture of water and particles with diameters less than 60 microns. Pass a parallel beam of light through the cylinder and let

I_0 be the intensity of the incident light, and
I be the intensity of the transmitted light.

Rose (1953) has shown that the relation between I_0 and I is given by the equation,

$$\ln \frac{I_0}{I} = kCl \sum_{d=0}^{D} K_x n d_x^2 \qquad (8)$$

where k depends upon the shape and orientation of the particles, n is the number of particles of size, d_x, per gram of sample, C is the concentration in grams per cubic centimeter, l is the length of the light path in the vessel, and K_x is the ratio of the light obscuring power of a particle of diameter, d_x, to that for the same particle if the ordinary laws of geometrical optics were applicable (Rose, 1953, p. 67). In any particular experimental situation, k, C, and l are constants, and values for K_x may be obtained from a curve provided by Rose. The particles are dispersed in the water and readings of I are then taken at known times t_1 and t_2, etc. The times are converted to the corresponding particle size by the use of Stokes' law.

A curve such as figure 3 is then plotted showing $\ln I_0/I$ as the ordinate and d_x as the abscissa. Let ordinates be erected at 1 micron intervals and consider two such successive ordinates which cut the experimental curve at m and n. The shaded area in figure 3 which is obtained analytically by multiplying the difference in the two ordinates by the mean diameter, d_x, is proportional to the weight of the material in the unit size range

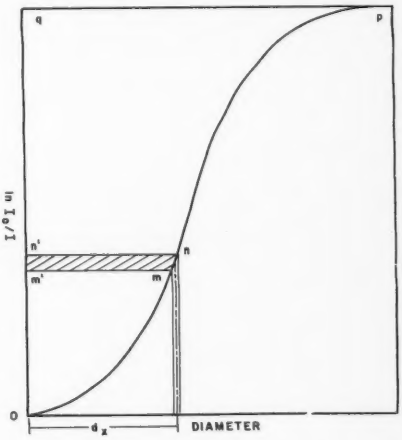

FIG. 3.—Experimental curve for photo-extinction method.

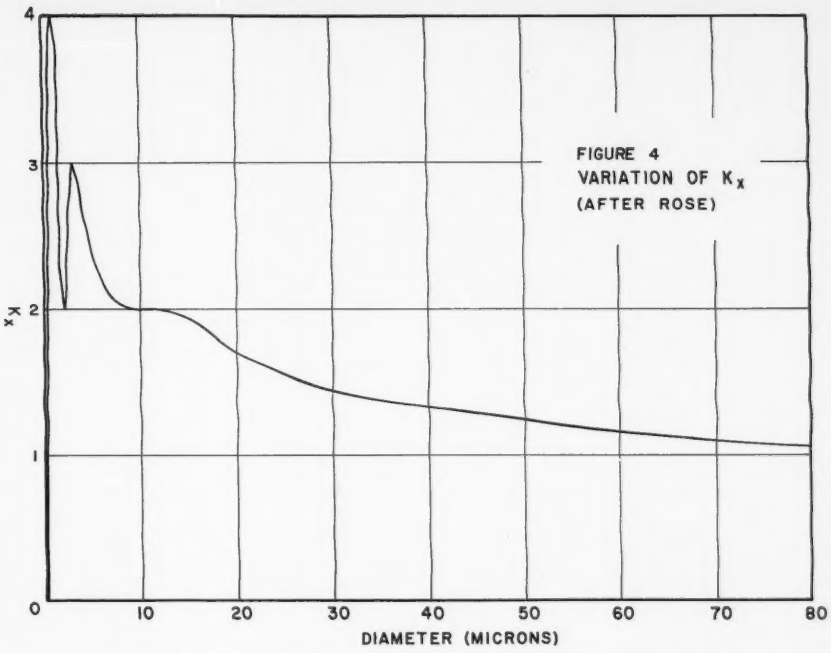

FIG. 4.—Variation of extinction coefficient, K_x, with particle size from 0 to 80 microns (after Rose).

$(d_n - d_m)$. The area *OpqO* is the sum of all such strips. Therefore the shaded area *mnn'm'*, expressed as a percentage of the total area *OpqO*, represents the size frequency on a *weight basis* of the sample at particle size d_x. The analysis of the experimental curve thus far has neglected the effect of changes in the extinction coefficient K_x, which for some sizes is quite appreciable.

The problem of variations in K_x is essentially that of a dielectric sphere in an electromagnetic field and has been investigated both theoretically and experimentally (Rose, 1953, p. 75). Rose constructed a curve, which is here reproduced as figure 4, showing the values of K_x for a range of particle sizes from 0 to 80 microns. It is obvious that the coefficient approaches unity for large particles. The method of applying the correction for the extinction coefficient is to divide the value for the shaded area in figure 3, before summing, by the value of K_x corresponding to the diameter, d_x. The numbers thus obtained represent the true weight percentage of particles in the unit size interval centered at d_x.

The following assumptions were made in the derivation of equation (8):

1) the particles are completely opaque;
2) there is no reflection between the particles or the vessel walls and the particles; and,
3) the factor K_x includes all deviations in light obscuring power from that given by the usual laws of geometrical optics.

Rose examined experimentally all of these assumptions and found that under certain conditions, they were satisfactorily fulfilled. The particles behave in a manner quite analogous to a lens. Rose shows through simple lens theory that the requirement for opacity is satisfied provided that the recep-

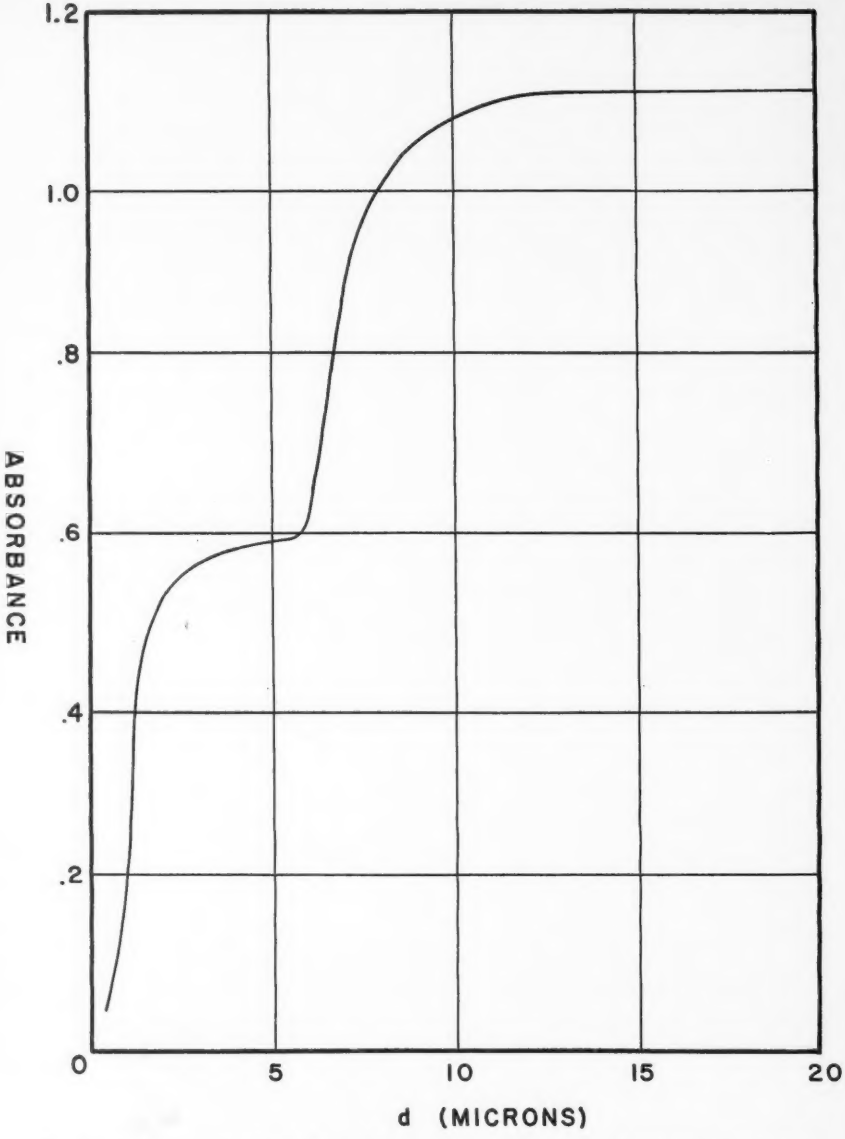

FIG. 5.—Sedimentation curve of quartz from which particles 3 to 6 microns and those greater than 8 microns have been removed (after Talvitie and Paulus).

tion is suitably restricted and a sufficient difference exists between the index of refraction of the particles and that of the liquid medium. Water is commonly used and provides good optical contrast for most of the particles of geological interest. A stop provided in the apparatus (fig. 6) serves both to limit the solid angle of the receiver and to eliminate the reception of scattered light. The specific value for the solid angle given by Rose (1953, p. 70) is 2.5×10^{-4} steradians, but for most particles encountered in the geological sciences it appears that larger values of the solid angle may be used without introducing excessive errors. Rose demonstrates both theoretically and experimentally that the above assumptions are satisfied for particles in the 2–60 micron size-range when the angle of reception is suitably restricted. The writer's experimental work corroborates these findings.

Talvitie and Paulus (1956) were interested in effects of inhaled dust particles upon the human body. They were predominately concerned with particles whose diameters were less than 5 microns, hence they constructed a recording photometric particle-size analyzer primarily for the 0–5 micron range. For the experimental demonstration of their analyzer, a sample of quartz dust was analyzed in which the particles between 3 and 6 microns and those greater than 8 microns had previously been removed. The resulting curve is reproduced in figure 5, with the term absorbance equivalent to $\ln I_0/I$. The removal of the 3 to 6 micron particles provides a rather severe discontinuity in the size distribution of the quartz dust. The faithfulness with which the equipment depicts the discontinuities at the 3, 6, and 8 micron points is certainly indicative of the validity of the PE method.

APPARATUS

The apparatus for the PE method is shown schematically in figure 6. The basic equipment consists of a small lamp, a lens, various stops, a sedimentation cell, a photoelectric cell, and a microammeter. The lamp is placed at the focal point of the lens to provide a parallel beam of light. Two stops (about $\frac{3}{8}'' \times 1''$) are used to provide a narrow slit of light and thus limit the vertical height of the beam. The stop between the cell and the photoelectric tube is necessary to eliminate the reception of scattered light and also limit the angle of reception. The sedimentation cell is a $2 \times 4 \times 8$ cm parallelopipedon. The photoelectric tube is a Weston model 594 YR photronic cell and the meter is a Simpson Model 374 microammeter. The particular phototube used, which is of the photovoltaic type, possesses the following advantages: it requires no outside voltage source, thus eliminating the need for a regulated power supply or batteries;

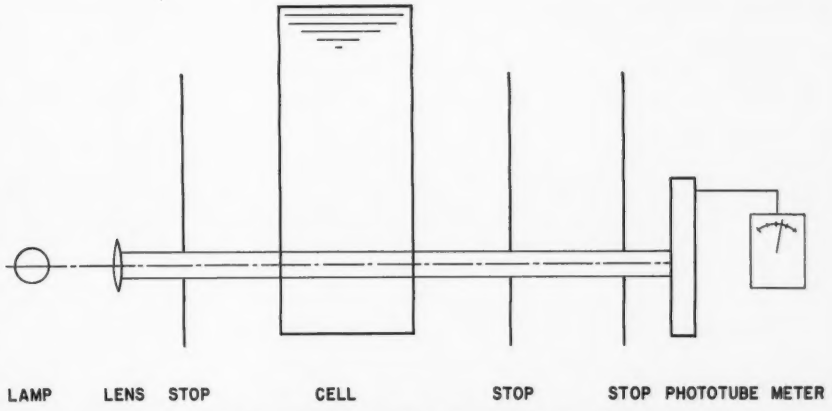

FIG. 6.—Photo-extinction equipment (schematic).

it provides a rather high microcurrent output for low light input; and, for an external circuit resistance of 200 ohms or less, the current output is directly proportional to the light input (Zworykin and Ramberg, 1949, chapter II). The model 374 meter is used because it has low internal resistance, convenient scale divisions, and sufficient accuracy for this purpose. The lamps commonly used with binocular microscopes are quite adequate and, when used in conjunction with storage batteries, provide a very stable light source.

The apparatus described above, which was used to obtain the experimental data for this thesis, represents the very minimum amount of apparatus necessary to obtain a size distribution by the PE method. However, as reflected by the experimental curves in figures 7, 8, and 9, the results are in general very good.

PROCEDURE

In order to demonstrate the PE method, the procedure for obtaining the cumulative curve shown in figure 7 is traced:

1) Record I_0 for liquid only in the cell.
2) Disperse the sample in the 1/100 N NaCl solution by shaking. The NaCl electrolyte tends to prevent coagulation of the particles and to prevent their adherence to the container walls. The proper amount of sample to use is best determined by trial and error. With about full scale reading on the microammeter for I_0, the amount of the sample should be adjusted to give a reading of about 10 to 20 percent of full scale when the sample is first dispersed.
3) Record the values of the current, I, at the appropriate times.

The time required for the fall of particles of a specific size may conveniently be obtained from Stokes' law. Thus if a distribution curve based upon a 5 micron interval is desired, the times of fall corresponding to diameters of 60, 55, 50, $\cdots$, and 5 microns should be calculated.

4) Compute values for $\ln I_0/I$ and plot against the corresponding diameter, yielding a curve similar to that shown in figure 3. This experimental curve must now be analyzed to obtain the size distribution.
5) Computations are made as indicated in table 1.

DISCUSSION OF RESULTS

In order to demonstrate the application of the PE method in the field of geology, the size distributions of three different materials were obtained and in each case a comparison was made with those obtained by the microscope method. For one of the materials, results of the hydrometer and pipette methods are included in order to place all four methods on a comparative basis.

It is important to state at this point that no selection of the data to be presented was intentionally made, with two minor exceptions. Certain experimental data were obviously erroneous because of the presence of

TABLE 1

(1) Diam.	(2) Ordinate	(3) Diff. in Ord.	(4) (Mid Dia) × (Col. 3)	(5) K_z	(6) (3)/(5)	(7) (Mid Dia) × (Col. 6)	(8) %	(9) % Cum
0	0							0
		2	2	2.2	.91	.9	.0	
2	2							0
		5	15	3.5	1.42	4.3	.2	
4	7							.2
		2	10	2.4	.83	4.2	.5	
6	9							.7
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
					Total:	2007.2	100%	

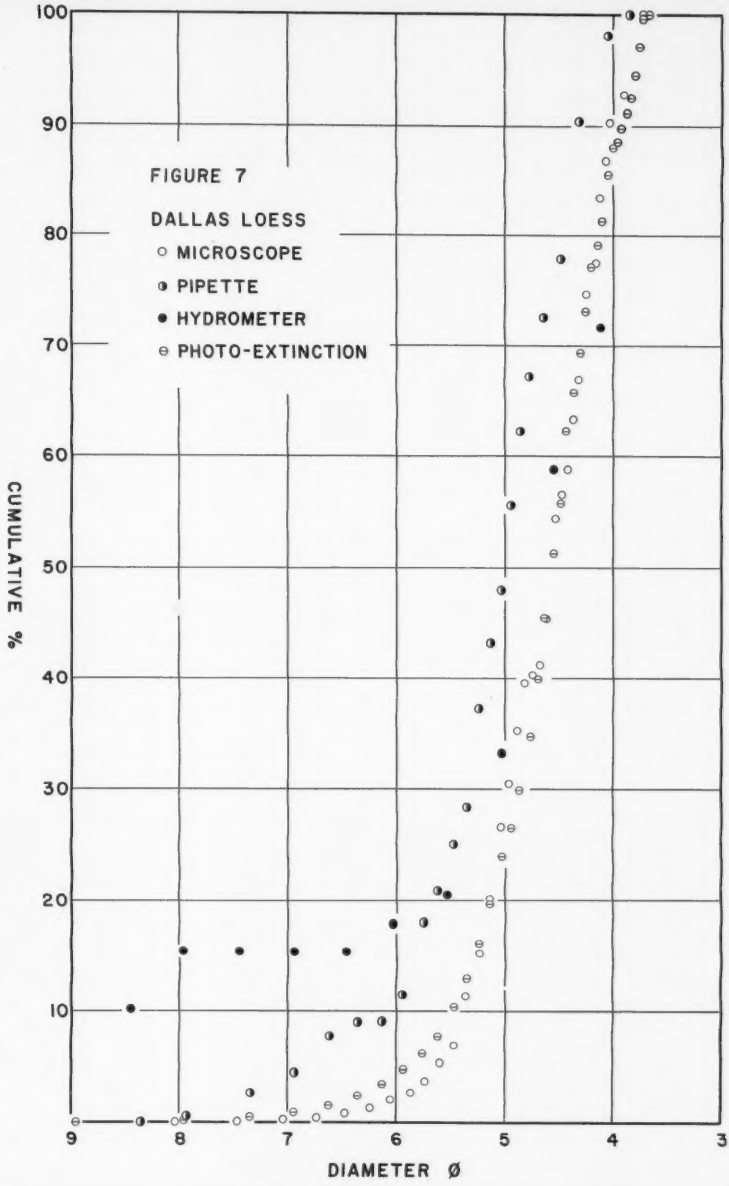

FIG. 7.—Comparison of analyses of Dallas loess by microscope, pipette, hydrometer, and photo-extinction methods.

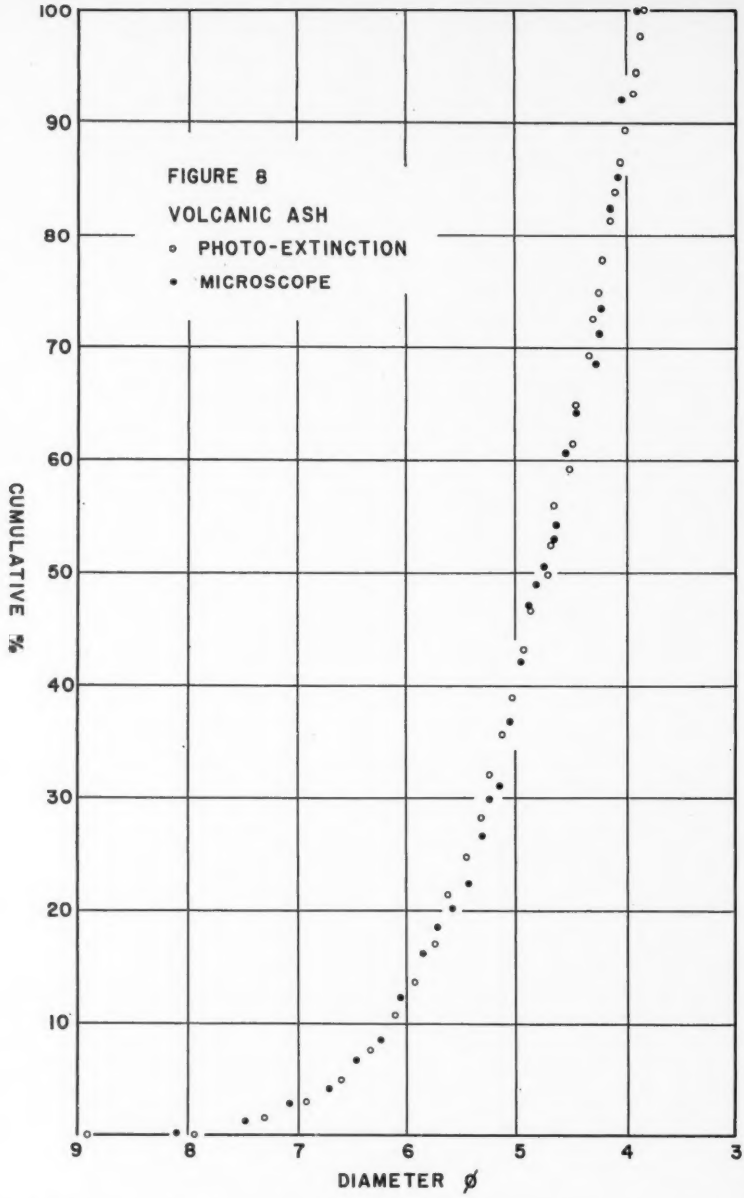

FIG. 8.—Comparison of analyses of volcanic ash by microscope and photo-extinction methods.

air bubbles in the cell or the adherence of particles to the cell walls. The air bubbles fulfilled all the requirements for small particles and thus caused the number of fines to appear to be too large. The use of distilled water which previously had been heated and allowed to cool to room temperature eliminated the air bubbles. A second source of difficulty arose from the tendency of smaller particles, after dispersal, to cling to the vessel walls, again causing the number of small particles to appear to be too large. This adherence of particles was probably caused by static electricity on the surface of the sedimentation cell. This problem was eliminated by using a 1/100 normal sodium chloride solution for the medium.

The material referred to as "Dallas loess" consists of grains carried to Dallas, Texas, by various dust storms. It was collected from a housetop and then sieved to remove the wood fibres. A second sample composed of volcanic ash came from the "Tertiary Lake beds" of Middle Park, Colorado, approximately 2 miles northeast of Kremmling. The silt sample was obtained from a bar in the Colorado River at Lee's Ferry, Arizona. All samples were sieved through a #325 screen to limit the size range and then divided with an Otto Microsplit. Analyses of the size distribution for the individual samples were obtained by various methods for comparative purposes. The results are shown in figures 7, 8, and 9 with the diameters plotted in phi units.

Dallas Loess. The Dallas loess was analyzed by the microscope, the pipette, the hydrometer and the PE methods. Eight hundred particles were measured under the microscope using class intervals of 1.8 microns and the resulting size frequency distribution was converted to a weight frequency distribution by equation (2). The curves for the Dallas loess are shown in figure 7. Irregularities in the cumulative curve obtained from the microscope data may be attributed to the counting of a finite number of particles and could theoretically be reduced by counting many more particles. The additional work, however, is unwarranted in view of the very large number that would have to be counted.

The data obtained from the PE method agree quite well with the distribution obtained from the microscope. The pipette method departs somewhat from the microscope standard while the hydrometer method seems to be the least accurate of the methods. The most serious departure of the PE curve from that of the microscope is for particles larger than 60 microns. This is not too surprising, nor alarming, however, in view of the fact that for these sizes neither method is particularly accurate. The microscope method is somewhat unreliable for the upper portion of the range because of the small number of particles of large size encountered in counting a random sample. On the other hand, the departure of the PE method from the true distribution in this range may be attributed to difficulties in accurately measuring the times of fall for the larger particles. The sedimentation of larger particles begins to cause a change in the meter reading after about 10 seconds. Small errors in reading the times of fall thus cause fairly large errors in the corresponding Stokes' diameters. The choice of a "zero-time" also becomes critical for the larger particles. The simplest and most practical method of obtaining a uniformly dispersed suspension is to thoroughly shake the containing cell. This, however, establishes turbulence in the medium which continues for a short time after the shaking has been discontinued and introduces some uncertainty as to when one should start measuring time.

Volcanic Ash. The PE distribution for the volcanic ash is compared in figure 8 with that obtained by the microscope. These data indicate a very close agreement between the two methods. It should be noted at this point that the ash consisted essentially of "two-dimensional" particles. The cumulative curve for the weight distribution derived from the microscope count was obtained by the use of equation (3) which introduces d^2 as a weighting factor. In obtaining the data for the ash, 314 particles were counted.

Lee's Ferry Silt. Two runs with the PE equipment were made on the sample from Lee's Ferry for the purpose of showing the reproducibility of results. The cumulative curves displayed in figure 9 indicate that the method yields data which can be reasonably well duplicated.

The results of a microscopic analysis of

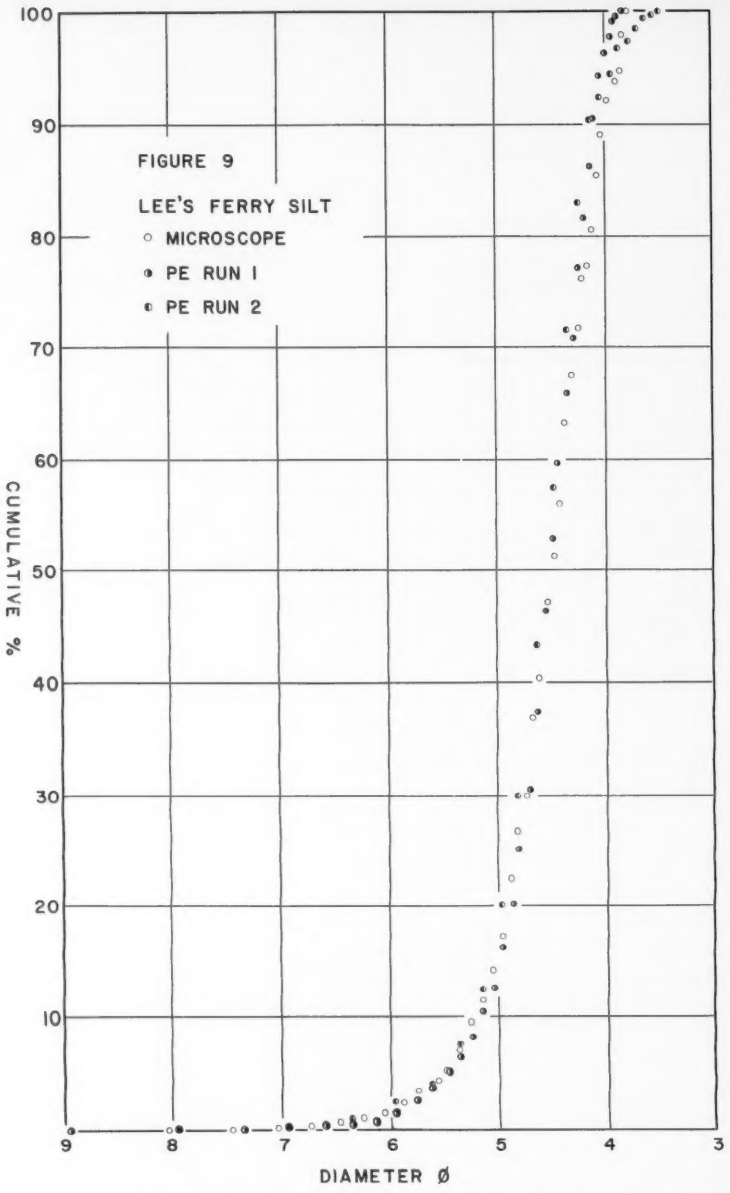

FIG. 9.—Comparison of analyses of Lee's Ferry silt by microscope and photo-extinction methods.

1692 particles are shown for comparison. Again, the PE method and the microscope method agree quite well.

CONCLUSIONS

The present working standard for the measurement of silt-size particles by geologists is the pipette method. Objections to this method are that insertion of the pipette disturbs the system, withdrawal of the sample also affects the system, considerable experience is required for satisfactory results, resolution of the data is limited, and the use of automatic recording equipment is precluded.

The photo-extinction method which measures the change of intensity of transmitted light overcomes these obstacles. Rose demonstrated the validity of the method on both theoretical and experimental bases. Data obtained by the writer indicate that the photo-extinction method yields results which agree very well with those obtained by the reference standard of counting with the microscope. The method combines a modest initial cost with decreased time and effort for accurate particle size analysis and also offers the possibility of automatic recording. The photo-extinction method is a new tool of considerable value to geology for the measurement of silt-size particles.

ACKNOWLEDGEMENTS

The writer wishes to thank the faculty members and his fellow graduate students of the Department of Geology at Southern Methodist University who freely gave assistance and valuable suggestions. In particular, Dr. Eugene Herrin first suggested the problem and subsequently provided guidance. The author is especially indebted to his wife, Mrs. Dorothy Simmons, who assisted in gathering data. Dr. Raymond Siever of Harvard University critically read the manuscript and suggested improvements.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 29, NO. 2, PP. 246–250
FIGS. 1–3, JUNE, 1959

DESCRIPTION OF THE MACKERETH PORTABLE CORE SAMPLER[1]

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ABSTRACT

The Mackereth core sampler is a portable corer capable of collecting fine-grained bottom samples from lakes and shallow seas at depths up to 300 feet. At the sampler's present stage of development cores up to 20 feet in length with a diameter of 1½ inches can be collected. The corer operates as a piston which is pushed into the sediments by compressed air. The corer is held on the surface of the sediment for the duration of the coring operation by the hydrostatic pressure. When the sample has been taken the corer is raised to the surface by means of compressed air.

INTRODUCTION

The author recently began a study of the late-glacial sediments found in cores collected from the floor of Windermere, the largest lake in the English Lake District. This short paper describes the coring apparatus used in that study.

The cores were collected from the lake floor by means of the Mackereth Core Sampler. The corer is about 25 feet long. In operation, use is made of the hydrostatic pressure near the lake floor, and the core is taken by means of compressed air. This corer has many advantages over other corers available to sedimentologists, the most noteworthy being its portability and the length of core it can take. Two men using a small boat can operate the corer; and at its present stage of development, a core 19 ft 6 ins long can be obtained. It may be operated at depths up to 50 fathoms with ease, and depths up to 100 fathoms should present no great difficulties.

A detailed description of the construction of this corer has been published by the inventor (Mackereth, 1958); a general description of its construction is given here together with details of operation of the corer.

COLLECTION OF CORES

General description of the corer. The corer consists of two metal tubes approximately 20 feet long, one tube within the other, and an anchor chamber 1 foot 6 inches in diameter and 4 feet long (fig. 1). The outer tube (A) is made of stainless steel and has an external diameter of 3 inches, with a wall thickness of $\frac{1}{16}$ inch. The inner tube (B), which takes the core, is made of duralumin and has an external diameter of 2 inches, with a wall thickness of $\frac{1}{16}$ inch. The inner tube is attached to a piston (C) and can slide past an inner piston (D) which is attached to the top of the outer tube by means of a narrow innermost tube (E). The anchor

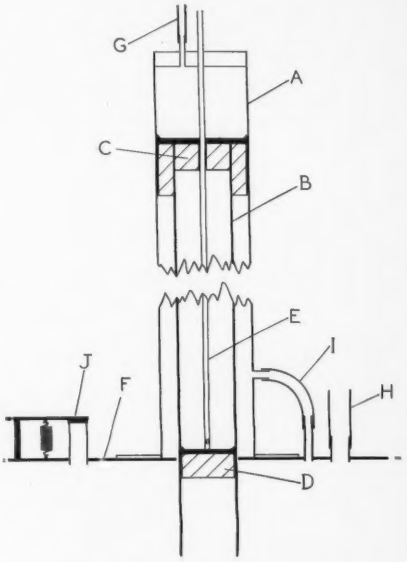

FIG. 1.—Diagram of main features of the Mackereth core sampler. Description in text.

[1] Manuscript received December 26, 1958.

chamber (F) is fixed to the lower part of the outer tube. In operation an air pressure hose (G) is attached to the top of the outer tube; and a hose (H), which is connected to a pump, is attached to the top of the anchor chamber. A short pipe (I) leads from the lower part of the outer tube to the top of the anchor chamber, and an air release valve (J) is also fitted to the top of the anchor chamber.

A recent development is the addition of a compass to the corer. The compass is attached to the corer near the top of the outer tube and is locked, when the corer is in operation, by air pressure. The air is taken from the air pressure hose which is attached to the top of the outer tube. The needle of the compass swings freely until the core is taken. Then, as the air under pressure pushes the core tube into the sediment, the same air pushes a piston which locks the compass needle by raising the needle from its pivot.

A second development is the addition of an extension to the core tube. The extension increases the depth of penetration of the corer though an equivalent length of sample at the surface is not collected. The extension is achieved by adding a length of metal tubing to the core tube and extending the innermost tube and fixed piston the required amount.

Operation of the corer. The corer is lowered to the lake floor by means of a nylon rope; the two hoses are payed out at the same time. Small floats are usually attached to the rope and to the top of the corer to facilitate this operation. When the corer has reached the lake floor a slight tension is retained on the rope, this tension and the small floats maintain the corer in a vertical position regardless of the topography of the lake floor (this has been checked by means of an echo-sounder). The water in the anchor chamber is now pumped out through the hose (H, fig. 1) extending from the top of the anchor chamber, and the hydrostatic pressure forces the chamber into the sediment of the lake floor. It is important that the anchor chamber be completely pumped out. That this has been attained is indicated by a change from clear to muddy water at the outlet of the pump. The hose is sealed off and compressed air is forced into the top of the outer tube by means of the air pressure hose (G). A pressure which is 100 lb./sq. in. greater than the hydrostatic pressure present at the lake floor is usually required to carry out this part of the operation. When the piston at the top of the core tube is pushed past the small pipe (I) from the outer tube to the anchor chamber, air escapes from the outer tube into the top of the anchor chamber. When the pressure in the chamber exceeds the hydrostatic pressure, the anchor chamber is lifted out of the sediment on the lake floor and the corer and core are raised to the surface of the lake by means of the buoyancy of the trapped air. The air release valve acts during the ascent; some air is released thus avoiding an excessive rate of ascent. The valve is held closed by a spring when the corer rests on the lake floor, but it is pulled open by a weight on a chain when the corer has ascended to a distance above the lake floor greater than the length of the chain. The chain should be longer than the length of the extended core tube, otherwise some buoyancy will be lost before the core tube is clear of the sediment.

The sequence of events is illustrated in figure 2:

I. The anchor chamber rests in contact with the sediment on the lake floor. The corer is supported by a rope, and the hoses from the anchor chamber and the top of the corner are connected to a pump and to a supply of compressed air in the boat (see inset).

II. The water trapped in the anchor chamber has been pumped out, and the hydrostatic pressure has pushed the chamber into the sediment. (If the extension is fitted to the core tube this will be pushed into the sediment at the same time.) The hose used to pump out the water is sealed, and the core is about to be taken.

III. Compressed air has been admitted into the space between the piston at the top of the core tube and the outer tube, and the core tube is being pushed into the sediment. At the same time the compass needle has been raised into the locked position. The hydrostatic pressure keeps the anchor chamber firmly fixed on the lake floor.

IV. The core has been taken, and compressed air has entered the anchor chamber

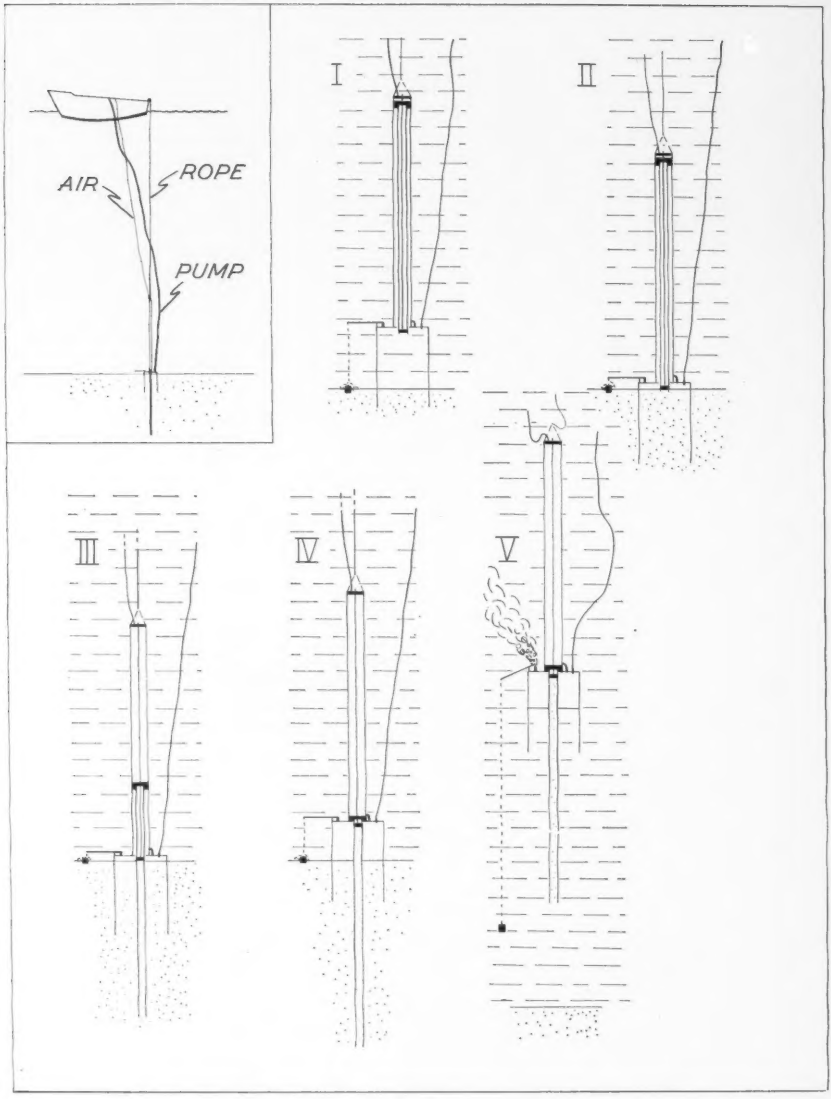

FIG. 2.—Operation of corer. Explanation in the text. Inset shows usual working position.

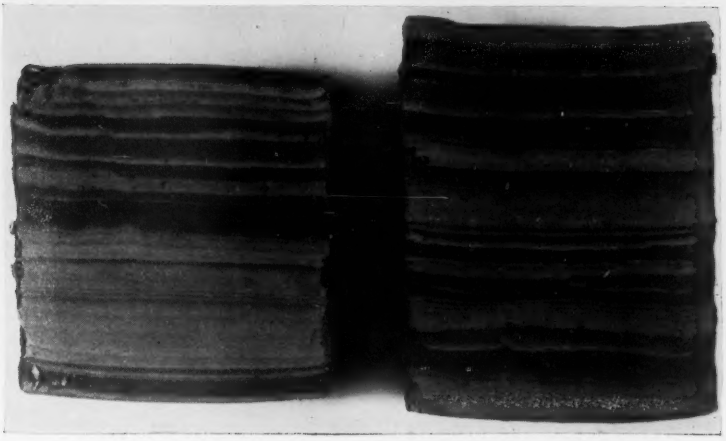

FIG. 3.—Parts of cores taken with the Mackereth core sampler. Width of each specimen about 1½ inches.

from the outer tube by means of the short pipe (I, fig. 1). The air pressure, being greater than the hydrostatic pressure, is raising the anchor chamber from the lake floor.

V. The corer is now rising to the surface, being lifted by the buoyancy of the air trapped in the anchor chamber. Some of the air is escaping from the chamber through the air release valve.

Extraction of the core.—When the corer reaches the surface it is lifted into the boat. Until the corer is in the boat a small amount of compressed air is still allowed to enter the corer to give it buoyancy at the surface. Once in the boat; the corer can be taken to the lake shore where the core can be extracted from the corer.

Extraction is carried out by pumping water into the space at the top of the core tube between the fixed piston (D, fig. 1) and the piston at the top of the core tube (C, fig. 1). The water passes into this space through the innermost tube (E, fig. 1). The water, under pressure, forces the piston at the top of the core tube up the outer tube and the core tube is thus retracted. As the core tube is retracted, the core is simultaneously ejected into trays or containers. If orientated cores are required the apparatus should be placed so that the North-South line of the compass on the corer is in the vertical position. On extraction the vertical plane through the cores as they rest in trays is thus aligned north to south.

Each core sample is usually placed in four trays, each tray being about 5 feet 6 inches long. If the cores are to be preserved they should be wrapped in cellophane paper, sealed with tape, and placed in a cold-room as soon as possible after extraction. If the cores are to be examined for sedimentary structures as soon as they are collected, they should be allowed to dry out to some extent. The rate of drying depends, in part, upon the grain size of the sediment in the cores, but usually two to three days are required before all the sedimentary features can be seen. A typical example of laminated sediment is shown in figure 3.

CONCLUDING REMARKS

This corer should prove to be a useful new tool for sedimentologists studying the unconsolidated, fine-grained sediments of lakes and shallow seas. It has many advantages over other corers capable of performing the same operation. It needs no special rig and can, therefore, be operated from a small boat. At its present stage of development it is not suitable for collecting cores of material coarser than sand grade;

water saturated sand is lost from the core tube as the apparatus is raised from the bottom sediment. The addition of a trap such as a spring core catcher at the open end of the core tube would retain the coarser, non-cohesive sediments.

ACKNOWLEDGEMENTS

The author wishes to thank John Mackereth, the inventor of the Mackereth Core Sampler, for his permission to write this account of the operation of the corer. The author also wishes to thank the Director and staff of the Windermere Laboratory of the Freshwater Biological Association for their valuable cooperation and assistance throughout the coring operations, and to acknowledge a grant from the Central Research Fund of the University of London.

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JUNE, 1959

SIGNIFICANCE OF STYLOLITES IN PERMEABLE SANDSTONES[1]

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ABSTRACT

The occurrence of stylolite seams in permeable sandstones indicates that solution is localized by the material in clay partings rather than by freer circulation along bedding planes. Cementation may be commonly related to stylolite formation as the dissolved material may be redeposited within the bed to form the cement.

The occurrence of stylolite seams along definite surfaces approximately parallel to bedding has generally been attributed to freer circulation of water along bedding planes. Stockdale (1936, p. 132) stated that the "formation of stylolites is best favored in soluble strata that are reasonably compact and fine grained, compelling movement of ground waters in concentrated amounts along restricted and especially favored channels." Most of the argillaceous and carbonaceous material along seams was considered to represent a residual accumulation left after solution of the more soluble constituents in the rock, but in no way a cause of solution.

The first indication that material such as clay promoted pressure solution was found in the St. Peter Sandstone where greater solution occurred in argillaceous zones (Heald, 1956a, p. 23). Thomson (1959) observed a similar situation in Silurian sandstones. The discovery of microstylolites along carbonaceous bands entirely within individual oölites further indicates the importance of foreign material in promoting pressure solution (Kanes, 1958).

The writer has recently found well-developed stylolite seams with clay[2] coatings in highly permeable sandstones (table 1). These occurrences differ from those previously reported by Heald and also those reported by Thomson in that solution was localized along definite seams rather than at grain contacts throughout clay-bearing beds. Solution must have been promoted by clay which occurred along original partings or by constituents associated with the clay. If circulation had been the controlling factor, solution would have taken place at grain contacts throughout the permeable beds rather than along definite seams. It might be argued that these beds were tight at the time of stylolite formation and that they were later decemented. However, the quartz overgrowths are euhedral and there is no evidence that their growth was impeded by any interstitial material. The truncation of quartz growths at the stylolite seams indicates that at least some growths were present during the last stages of stylolitic solution.

Although many stylolite seams occur in well-cemented sandstones of low permeability, there is no reason why the seams could not have started to form along clay partings while the sandstones were porous.

TABLE 1.—*Permeability and porosity of permeable sandstones with stylolite seams*

Sample No.	Distance from seam (cm)	Permeability[1] (Millidarcys)	Porosity (Percent)
1	4.0	134	26
2	1.5	193	22
3	1.0	183	18
4	0.5	40	11

[1] Permeability measured parallel to seams.

1. Pottsville sandstone, outcrop sample, Dellslow, W. Va.
2. Pottsville sandstone, outcrop sample, Sand Spring, W. Va.
3. Dakota sandstone, core sample, Grizzly Buttes Well #1 (Sec. 35, T. 15 N., R. 115 W.) Wyo.
4. Oriskany sandstone, core sample, Bruen Heirs Well #5, Kanawha Co., W. Va.

[1] Manuscript received November 3, 1958.

[2] The term clay as used in this paper includes clay minerals, carbonaceous material, iron-bearing minerals, and other fine grained material which may occur along stylolite seams.

The material dissolved along the seams could easily be deposited nearby as a cement and lead to the presently observed low porosity.

Discontinuous seams which in some rocks are only a few inches in length can better be explained by solution promoted by clay rather than by freer circulation along a parting. Advanced induration with nearly complete pore reduction would have to be assumed to account for circulation only along the partings. However, subsidence accompanying the solution along the short discontinuous seams would result in faulting at the margins of the seams in indurated rock. The fact that faults are normally lacking indicates that solution along the discontinuous seams occurred while the rock was little indurated and, therefore, before complete pore reduction.

A thick series of beds with only an occasional stylolite seam suggests that circulation is not the controlling factor in the stylolite development. No megascopic stylolite seams have been found in the Triassic rocks of the eastern United States except for a few very well-developed seams at one zone in the sandstone at Raven Rock, New Jersey (Heald, 1956b, p. 104). Presumably, circulation would have been much easier along the many bedding planes than along the sinuous clay-coated seams. The presence of pyrite on these seams instead of hematite, which is common in the sediments, suggests a compositional difference which favored stylolite solution at this one horizon. Similar examples of restricted stylolite formation can be found in several Paleozoic sandstones in the Appalachian area. The lack of stylolites in a formation in an area where well-formed seams occur in both younger and older formations could also be more easily explained by differences in the nature of the clay on the partings than by differences in circulation.

The original distribution of clay determines where most of the early pressure solution occurs. If the sediment were clean but with clay partings, definite seams would form along the partings and a minimum of solution would occur at grain contacts within the beds. If clay partings were lacking and moderate amounts of clay were uniformly distributed throughout the beds, solution would occur at grain contacts and definite stylolite seams would be lacking. Randomly distributed clay at a few grain contacts would produce only limited solution because support from adjacent clean grains would prevent continued penetration. The amount of pressure solution in highly argillaceous sandstones can not be easily ascertained, but locally if may be very large (Heald, 1955, p. 106).

It is not known exactly why greater solution occurs in the presence of clay and carbonaceous material. Thomson (1959) has suggested that potassium from clay promotes solution. Other constituents associated with clay or carbonaceous material may also play a part. In some areas, ash falls would furnish favorable conditions for the development of stylolite seams in sandstone. Release of alkalies during the diagenesis of the ash would promote solution of quartz at the horizon where the ash accumulated.

If the constituent in the clay causing solution were removed during stylolite formation, the seam would cease to enlarge when this constituent became exhausted. The size of the seams would therefore be related to the original amount of the constitutent which caused solution. The continued development of some seams while other seams in the same rock ceased to enlarge could also be explained by initial differences in the amounts of clay along the partings. With continued stylolite solution, clay which was within the beds would be added to the seams as the more soluble constituents dissolved. When the original clay on the parting becomes inert, the added clay may be the chief cause of further solution. If the new clay were unevenly distributed, it would produce irregularities in the seams by causing more solution on the side of the seam where it was added. Columns would become longer because more clay would be added on the side undergoing the greater solution. Relatively insoluble constituents irregularly distributed throughout a bed, of course, would also account for stylolite columns.

Stress required for pressure solution may not be as great as formerly believed. Within porous sandstone beds, stresses are relatively high because they are concentrated at the small contact areas between grains.

Stress along clay partings is evenly distributed over the parting and is therefore much less intense. In spite of these stress differences, solution is largely limited to the clay partings. The occurrence of practically undeformed mica next to quartz which has undergone considerable pressure solution also indicates that the stress required is not necessarily great. The excellent preservation of detail in plant fossils in coarse sandstones, such as *Lepidodendron* in the Pottsville sandstone, is partly due to pressure solution. Instead of penetrating the plant material, the detrital quarz grains underwent pressure solution in contact with the carbonaceous material and thus left a relatively smooth mold surface. If great stress had been required for this pressure solution, it is doubtful whether the finer markings would have been preserved. Nevertheless, some stress is required inasmuch as no solution occurs at unstressed contacts even where clay or carbonaceous material is present.

The lack of stylolites along a clay parting may be due to insufficient pressure, low temperature, or unfavorable clay composition. The rate of removal of the dissolved material would also be a factor in determining the extent of solution. If the dissolved material were not removed by precipitation or by circulating water, the high degree of saturation would prevent further solution.

Clay would not be a factor in initiating stylolitic solution along fractures across bedding. As most fracturing occurs after lithification and reduction in porosity, circulation would be limited to the fractures and under the appropriate stress conditions stylolites would form. If the sediment were clay-bearing, further solution might be aided by the clay as it reached the stylolite seam.

The fact that stylolite seams can form in porous sedimentary rocks is very significant in that the seams represent a potential local source of large quantities of cement. Under the theory of channeled circulation along partings, stylolite seams could not form until pore reduction was nearly complete; therefore, nearby seams could not have furnished the cement. Many writers have claimed that stylolites post-date induration. However, stylolites may start to form relatively early and actually be an important factor in promoting induration by supplying cement. The commonly observed truncation of the cementing material along seams would indicate that solution continued after the onset of cementation.

When more is known about the nature of the clay which produces solution, it should be possible to determine where stylolites would most readily form and thus areas of probable cementation could be outlined. Where the clay is lacking, more favorable porosity would be expected. Much of the vein filling in fractured sedimentary rocks also could have been derived from stylolites, inasmuch as clay-induced solution along seams can continue even after open fractures develop.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 29, NO. 2, PP. 254–259
FIGS. 1–4, PLATE 1, JUNE, 1959

THE ORIGIN OF STYLOLITES IN THE LIGHT OF A PETROFABRIC STUDY[1]

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ABSTRACT

Petrofabric analysis of authigenic quartz crystals in stylolites from Carboniferous limestone in North Wales has been undertaken. The results obtained support Stockdale's "Pressure-solution" theory.

INTRODUCTION

Although stylolites have been recognised for over a century and have been the subject of many papers in the last twenty years, the problem of their genesis is still discussed.

At present two diametrically opposed theories of stylolite formation command the greatest support, the "contraction-pressure" theory as proposed by Shaub (1939) and the "solution-pressure" theory of Stockdale (1922, 1943), of which the latter is the most widely accepted.

PETROFABRIC ANALYSIS

In order to determine the intensity of preferred orientation of the quartz crystals along the seams, five petrofabric diagrams (pl. 1) were prepared. The measurement of the attitude of the [0001] axes of quartz has been done with the aid of a Leitz U-5 universal stage.

Diagrams *a* and *b* each represent the results of the measurement of 200 quartz axes from two different specimens. The sections were cut approximately at right angles to bedding and parallel to the long axes of the stylolite columns. The maxima obtained appear to coincide with the direction of elongation of the "limbs" of the columns.

Diagram *c* illustrates the distribution of 200 grains of authigenic quartz in the matrix. The maxima are widely scattered, suggesting a random orientation.

Diagram *d*, again determined from a thin section cut at right angles to the bedding, illustrates the orientation of 200 quartz crystals at the apices of the columns. The almost complete cross girdle indicates a development of optic axes in the plane of the apex (i.e. the plane of the bedding), and emphasizes the development of quartz crystals at right angles to those along the "limbs."

Diagram *e* has been prepared from a section cut parallel to bedding and shows a major maximum in the centre, implying that the quartz optic axes have a preferred orientation parallel to the elongation of the column. This section confirms the homogeneity of the fabric of the quartz crystals.

INTERPRETATION OF OBSERVATIONS

In an inspiring paper, Dunnington (1954) shows that the evidence Shaub used to support his theory is inadequate and in many cases ill-founded. The evidence presented here suggests that at least some, if not all, stylolites developed by the "solution-pressure" mechanism after the compaction of the host rock.

OBSERVATIONS

During the summer of 1958 in the course of detailed mapping of Lower Carboniferous limestones in North Wales, numerous examples of stylolitic rock were collected. Two of the samples found throw new light on the origin of stylolites.

The specimens show stylolites occurring in a calcite mudstone. In one specimen in particular it was possible to recognise the relationship of the stylolite to bedding since there was an abundant faunal content above the seam (mainly foraminifers and occasional brachiopod fragments), while below the seam, calcispheres provided the only evidence of skeletal remains. (fig. 1.)

[1] Manuscript received November 20, 1958.

Authigenic quartz crystals, ranging in size from 50 to 500 μ, are concentrated along the stylolite seam, and the columns themselves range from 1.25 to 8.75 mm or more. There is no sign of any concentration of clay at the apices, but rather there is a marked concentration of quartz crystals at these points.

For the following reasons it is possible to recognise the crystals as being authigenic:

1. they are perfectly or almost perfectly idiomorphic;
2. many show a small nucleus of detrital quartz around which the idiomorphic quartz has developed in optical continuity; and,
3. abundant relic grains of calcite occur as inclusions in the quartz crystals and are often arranged in concentric layers parallel to the crystal outline.

The authigenic quartz crystals have evidently developed at the expense of the groundmass calcite, and the quartz crystals not only now occupy the entire seam but also display a distinct, preferred orientation. The c-crystallographic axes of the quartz crystals are aligned parallel or subparallel to the stylolite columns (fig. 2).

For descriptive convenience the trace of the columnar surfaces of the stylolite, in a section cut at right angles to bedding, will be resolved into "limbs" and apices and hereafter will be designated as such. The apices of the columns (fig. 3) display a different orientation pattern in that the authigenic quartz crystals develop at right angles to those along the "limbs," and in the plane of the apex.

Thin sections cut parallel to bedding and at right angles to the long axis of the stylolite columns show the majority of crystals to be basal or near basal sections (fig. 4), thus substantiating the previous remarks on the preferred orientation of the [0001] axes of quartz along the "limbs" of the columns.

On either side of the stylolite, the quartz crystals in the matrix of the limestone show no preferred orientation whatsoever.

Having established the fact that the authigenic quartz crystals along the stylolite seams display a distinct preferred orientation, three main conclusions follow:

(1) in order that the authigenic quartz

FIG. 1.—Stylolite in limestone collected from Eglwyseg Mountain, N. Wales. Small dark spots in the limestone on either side of the seam are authigenic quartz crystals. Magnification ×1.3.

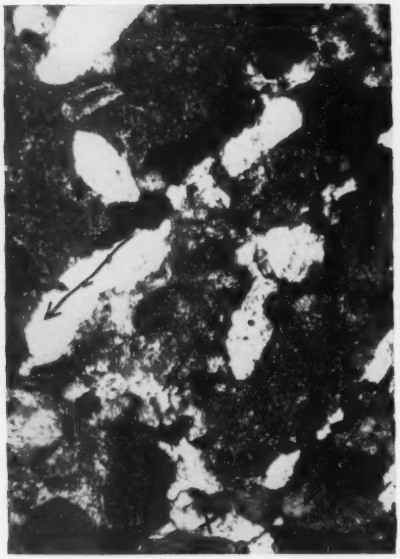

FIG. 2.—Photomicrograph illustrates the preferred orientation of authigenic quartz crystals along the limbs (indicated by arrows) of the stylolite. The apex (X) at the bottom right, shows the orientation of quartzes at right angles to those on the "limbs." (Crossed nicols ×65)

FIG. 3.—Photomicrograph shows the orientation of the quartz crystals at the apices compared with those on the "limbs." Two "limbs" are illustrated on the photograph and their elongation is indicated by arrows. The apex is marked by "X" and it is to be noted that here the crystals (mainly black on the photograph) are aligned more or less at right angles to those on the "limbs." (Crossed nicols ×65).

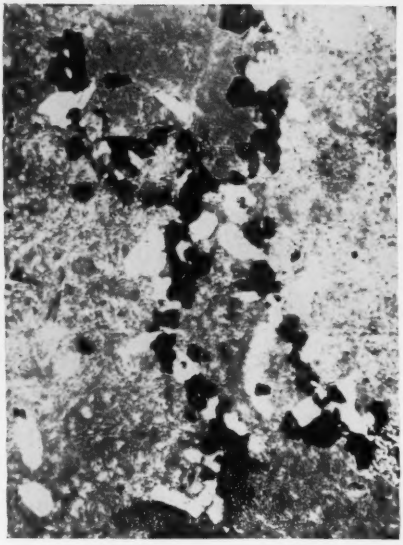

FIG. 4.—Photomicrograph of stylolite in a section parallel to bedding. The columnar structure of the stylolite is shown by the circular concentration of quartz crystals at the top of the photograph; the majority of sections seen are basal or near basal. (Crossed-nicols ×28).

PLATE 1.—Orientation diagrams.

a. 200 quartz axes from parallel "limbs" of the stylolite. The curved line indicates trace of bedding and the arrow the elongation of the "limbs." Contours 7-6-5-4-3-2-1-%.

b. As above, but from a different specimen and contours are +6-4-2-1%.

c. Fabric of the quartz crystals in the limestone on either side of the seam. 200 quartz axes measured and contoured at 4-3-2-1% intervals.

d. 200 quartz axes from apices of stylolite. Curved line indicates bedding and the arrow elongation of the "limbs." Contours +6-4-2-1%.

e. 200 quartz axes from stylolite "limbs." Section cut parallel to bedding. Contours +6-1-2-1%.

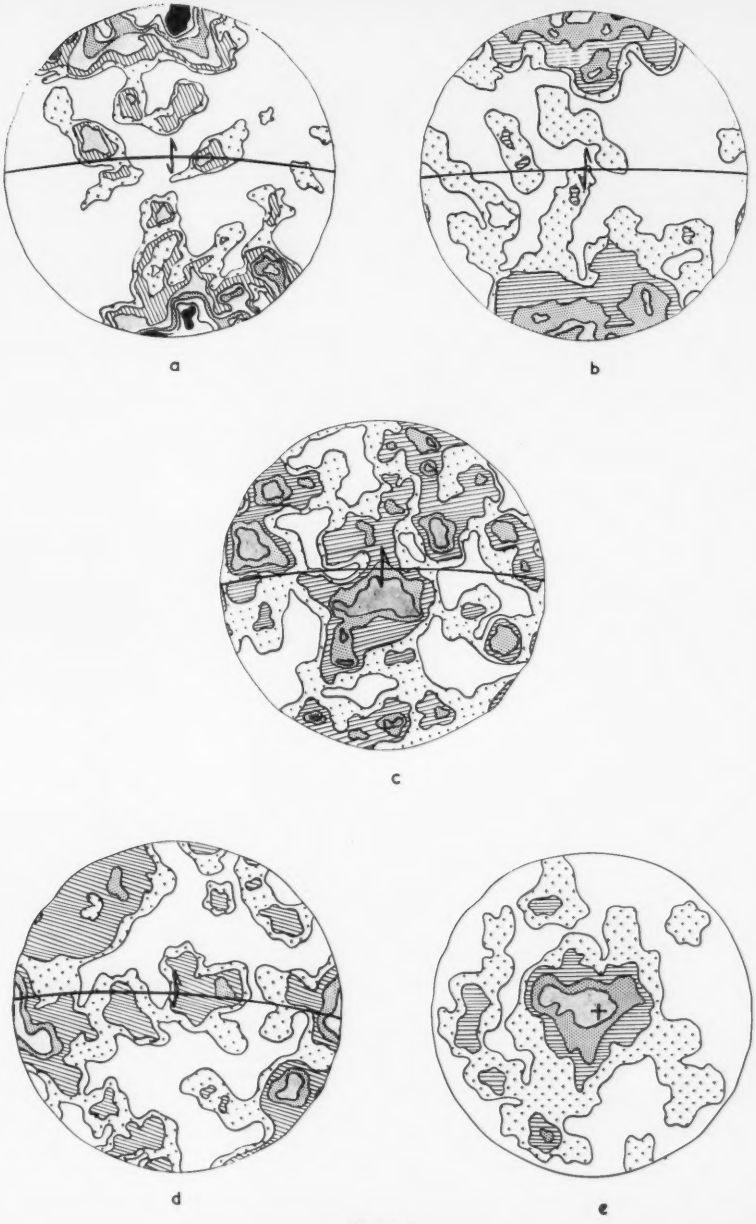

PLATE 1

←Explanation on facing page.

crystals might develop, there must have been solution and crystallization along the line of the stylolite;

(2) to establish a marked orientation of the [0001] axes of quartz, some directive force must have been operative during the growth of the crystals; and,

(3) the stylolite developed after induration of the host rock since the authigenic quartz crystals represent post-induration phenomena.

DISCUSSION

Direction of Pressure

Stockdale's theory, that some directive pressure has been active in the development of stylolites and that there has been sliding of the individual portions of one side of the stylolite into the dissolved out portions of the other, is supported by the preferred orientation of the authigenic quartz crystals along the columns.

According to the Trener α and γ rules of quartz orientation, the crystals may be oriented with their c-crystallographic axes either parallel to, or at right angles to the direction of greatest compressive stress. Sonder (1933) suggests that minerals tend to grow with their axes of greatest compressibility parallel to the direction of greatest compressive stress, and since the axes of greatest compressibility for low temperature quartz is perpendicular to the [0001] axis, then there will be an orientation of the optic axes at right angles to the stress (α-rule). Flinn (1956), however, finds that the optic axes of quartz may be parallel to the direction of greatest stress (γ-rule).

Assuming that the pressure has been operative in a direction parallel to the long axes of the columns, and therefore in the case in question effectively vertical, diagrams *a*, *b*, and *e* (plate 1) would appear to satisfy the Trener γ-rule and show pronounced maxima in "a." On the other hand, diagram *d* conforms with the type of orientation depicted by Trener (1906) to illustrate the α-rule.

It would seem that during the growth of the authigenic quartz crystals there has been an interpenetration of the "teeth" and "sockets" of the stylolite, and the resulting slip has caused an orientation parallel to the direction of movement (lineation in "a," conforming with the γ-rule. (Sander, 1932.)

The orientation of the quartz crystals at the apices, at right angles to those on the "limbs," may be readily explained by the fact that pressure will eventually be greatest at the crests and troughs of the stylolite seams; and since no slip movement is involved, one would expect to find a preferred orientation at right angles to the direction of pressure (α-rule).

Pressure has not been evenly distributed throughout the rock mass and must have been concentrated along the line of the stylolite since no preferred orientation is to be observed in the rock on either side of the seam.

The Role of Chemical Solution

Since the stylolite has developed on a minor bedding plane, this plane may have facilitated differential chemical solution under pressure which allowed the concentration of detrital quartzes along the line of the stylolite.

The authigenic quartzes occur as enlargements of detrital quartz fragments and, apparently, also independently of them. The silica may have been partly or wholly deposited from dissolved detrital quartz fragments, or perhaps from the special local action of connate waters.

These deductions are opposed to those of Shaub (1949) who, according to Dunnington (1954), "dismisses as commonplace and insignificant the evidences brought by many authors in support of the thesis of post-induration genesis in general, and the 'solution-pressure' theory of origin in particular."

Although Stockdale's evidence in support of the "pressure-solution" theory has so far not satisfied everyone, the evidence presented in this paper would suggest that his explanation of the mode of formation of stylolites is relevant and that the seams described above did develop according to his theory.

ACKNOWLEDGEMENTS

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 29, NO. 2, PP. 260–266
FIGS. 1–5, JUNE, 1959

DIAGENESIS OF LATE CAMBRIAN OÖLITIC LIMESTONE, MAURICE FORMATION, MONTANA AND WYOMING[1]

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ABSTRACT

Dolomitization of Late Cambrian oölitic limestone in the Maurice Formation followed lithification and preceded regional fracturing of the rock. The source of Mg-rich dolomitizing solutions is believed to have been connate waters from adjacent argillaceous sediments. Regional compaction forced these waters into the permeable oölite sands of the Maurice Formation. Fluid migration and subsequent dolomitization were controlled by effective porosity trends essentially parallel to bedding. Aragonitic oölite nuclei formed natural foci for dolomitization.

INTRODUCTION

Late Cambrian rocks in southern Montana and northwest Wyoming include the Maurice Formation, the Snowy Range Formation and the Grove Creek Formation (Dorf and Lochman, 1940). The Maurice Formation conformably overlies the shales and sandstones of the Middle Cambrian Park Formation and consists of a basal limestone-pebble conglomerate, platy limestone and shale member overlain by a massive, dolomitized oölitic limestone member. The upper member of the Maurice Formation is conformably overlain by shales and limestone-pebble conglomerates of the Snowy Range Formation (fig. 1).

The upper member of Dorf and Lochman's (1940) Maurice Formation is the "Mottled limestone" or "Gallatin cliff" described by Iddings and Weed (1894) and Peale (1896). Deiss (1936) included the unit in his description of the Pilgrim Formation in southern Montana and Yellowstone National Park.

The mottled limestone member of the Marurice Formation contains faunas of the *Crepicephalus* and *Aphelaspis* zones, suggesting temporal equivalence with the upper part of the Eau Claire Member of the Dresbach Formation in Wisconsin (Dorf and Lochman, 1940, p. 555). The Maurice Formation is correlated with the Pilgrim Formation of central Montana, part of the Boysen Formation of the Gros Ventre region, and part of the Hasmark Formation of western Montana (Lochman, 1949, p. 35).

Regional extent of the upper Maurice oölitic limestone is approximately 20,000 square miles. It is the most distinct lithologic unit in the Cambrian sequence, and it almost invariably crops out as a massive cliff. In southern Montana and northwest Wyoming the unit is oölitic and mottled (fig. 2). Mottling results from variable dolomitization of the oölitic limestone. The massive oölitic limestone member of the Maurice Formation thins eastward from the Gravelly Range (Mann, 1950) to the mouth of the Clarks Fork canyon (Wise, 1957). The unit is not recognized in the subsurface of the Big Horn Basin (Burke, et al., 1956). North from Crowfoot Ridge in the Gallatin Mountains, to the Bridger Range, the mottled limestone is readily recognizable in outcrop (Deiss, 1936; C. W. Wilson, 1934; J. T. Wilson, 1936; Dorf and Lochman, 1940; Skeels, 1936; McMannis, 1952, 1955). In northern Yellowstone National Park, the member is 100 to 140 feet thick and thickens gradually to the north, southwest, and west. East of the park, the member is 70 feet thick at the mouth of the Clarks Fork canyon (fig. 3).

Regionally, wherever the limestone is mottled it is oölitic. Mottling patterns are preferentially oriented parallel to bedding and are unrelated to fractures in the rock (McMannis, 1955, p. 3, fig. 1). Where the dolomitized oölitic limestone interfingers with argillaceous limestone-pebble conglomerates in the Bridger Range (McMannis, 1952), dolomitization is limited to the

[1] Manuscript received September 13, 1958.

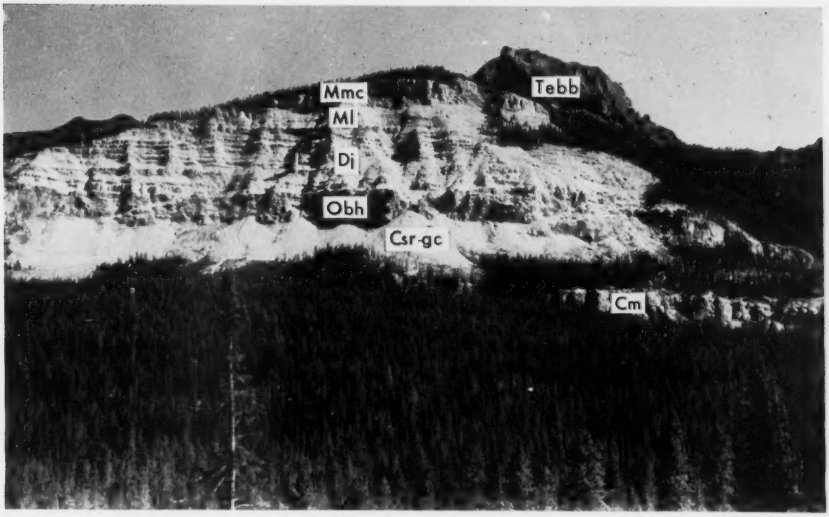
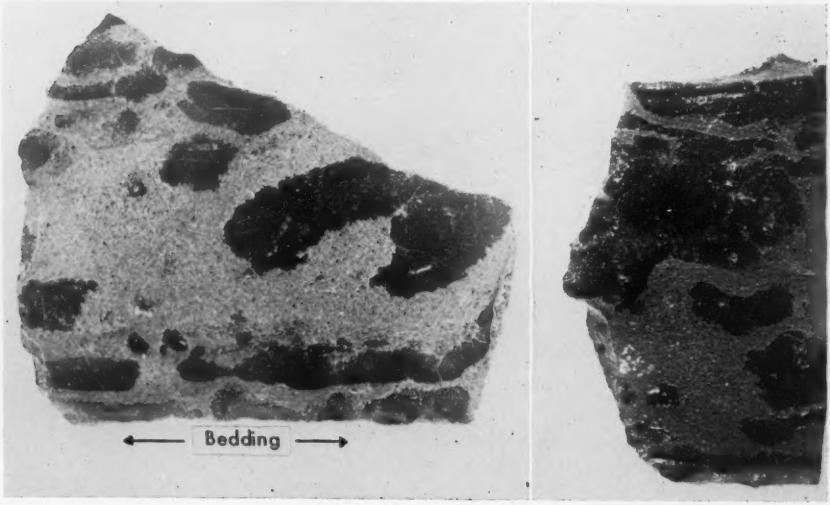


FIG. 1.—Paleozoic section, north flank Abiathar Peak, northeast Yellowstone National Park. Cliff-forming member of the Maurice Formation (Cm), overlain successively by Snowy Range and Grove Creek Formations (Csr-gc), Ordovician Bighorn Formation (Obh), Devonian Jefferson Formation (Dj) and the Mississippian Lodgepole (Ml) and Mission Canyon (Mmc) Formations. Middle Eocene Early Basic breccia (Tebb) unconformably overlies the Paleozoic sequence.



A B

FIG. 2.—Mottled limestone, upper member Maurice Formation, northern Yellowstone National Park. (A) Polished specimen, 5″ long, with dark gray oölitic limestone and tan dolomite; (B) specimen etched in dilute HCl.

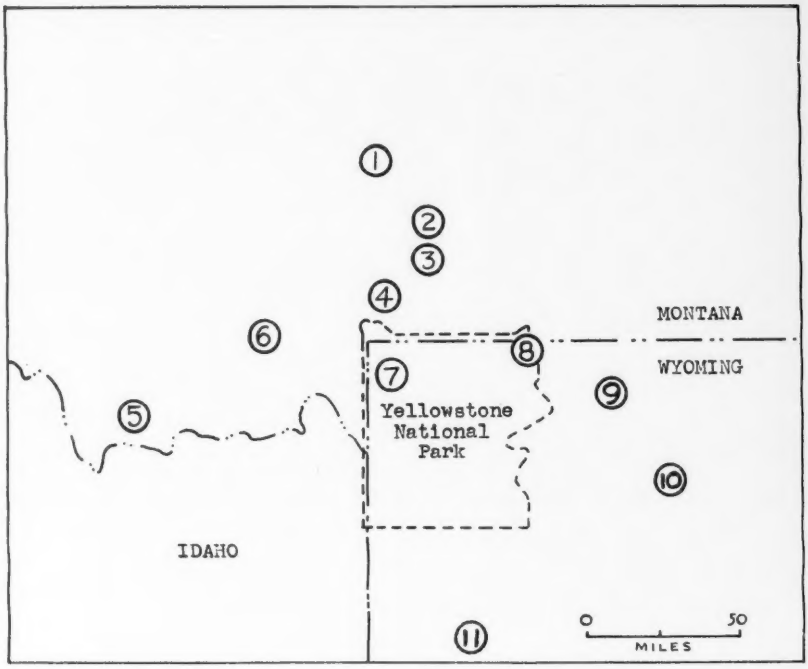


FIG. 3.—Locality Index.

(1) Bridger Range area.
(2) Trail Creek-Canyon Mountain area.
(3) Mill Creek-Stillwater area.
(4) Cinnabar Mountain.
(5) Lima region.
(6) Gravelly Range area.
(7) Crowfoot Ridge, Gallatin Mountains.
(8) Abiathar Peak, Yellowstone National Park.
(9) Mouth of Clarks Fork canyon.
(10) Big Horn Basin (Oregon Basin) subsurface.
(11) Gros Ventre region.

oölitic limestone. In northern Yellowstone National Park similar relations exist. Aphanitic, argillaceous, carbonate rocks adjacent to the Maurice oölitic limestone are not dolomitized. There appears to be a direct relation in these rocks between primary effective porosity and susceptibility to dolomitization.

PETROGRAPHY

The most striking characteristic of the cliff-forming member of the Maurice Formation is the mottled gray and brown appearance of the limestone in outcrop. Megascopic and microscopic analyses indicate that the gray areas are unaltered oölitic limestone and the brown areas are wholly or partly dolomitized limestone (fig. 4). The dark gray relatively unaltered areas consist of tightly packed oölites and finely crystalline calcite matrix. Most of the oölites are recrystallized; some occur in "ghost outline." Other oölites have their central portion dolomitized. The areas of tightly packed oölites are in many places surrounded by an irregular zone of coarsely crystalline, clear calcite with scattered oölites. In some places, the coarse, clear, calcite grains have rounded edges, and none appears to be in optical continuity with adjacent grains. Oölites in the coarse, clear, calcite zone are more commonly dolomitized

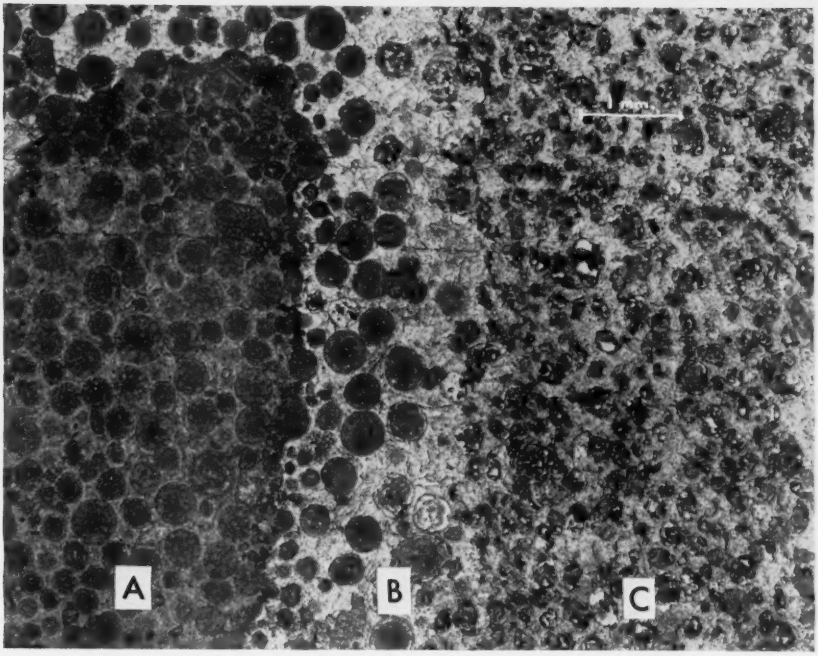


FIG. 4.—Zonation of mottled limestone: (A) Gray oölitic limestone; (B) coarse clear calcite zone; (C) tan dolomite. Plain light.

than oölites that are tightly packed and in a finely crystalline matrix. The light brown areas of the rock consist of clusters of dolomite rhombs representing replaced oölites in a finely crystalline matrix of calcite that has been variably dolomitized. Where dolomitization has been extreme, the rock consists of a fine mosaic of dolomite rhombs that do not have preferred orientation. The areas of intense dolomitization commonly invade the zones of coarse, clear calcite with scattered oölites and corrode the margins of the areas of tightly packed oölites.

Stylolites are common in the mottled limestone occurring as irregular, thin, linear zones of concentrated dolomite rhombs (fig. 5). Dolomitization of the surrounding rock is not related to these tiny fissures. It is believed that the dolomite rhombs were concentrated by solution of the surrounding calcite matrix prior to collapse of the solution channel.

DIAGENESIS

Interpretation of diagenesis in the Maurice Formation mottled limestone member is limited to determining (1) the time of dolomitization relative to lithification, (2) the source of Mg-rich solutions causing dolomitization and (3) the physical controls affecting the diagenetic process.

McMannis (1955, p. 1395) studied the Maurice Formation in the Bridger Range, Montana, and concluded that "dolomitization was probably accomplished after deposition, but before or during solidification." Dolomitization of the recrystallized calcite matrix suggests that the rock was lithified, at least in part, prior to dolomitization. Owing to the complexity and selectivity of dolomitization, however, it is possible the matrix was dolomitized prior to selective calcite recrystallization. If this occurred, one might expect to find corroded or partly replaced margins of the dolomite rhombs.

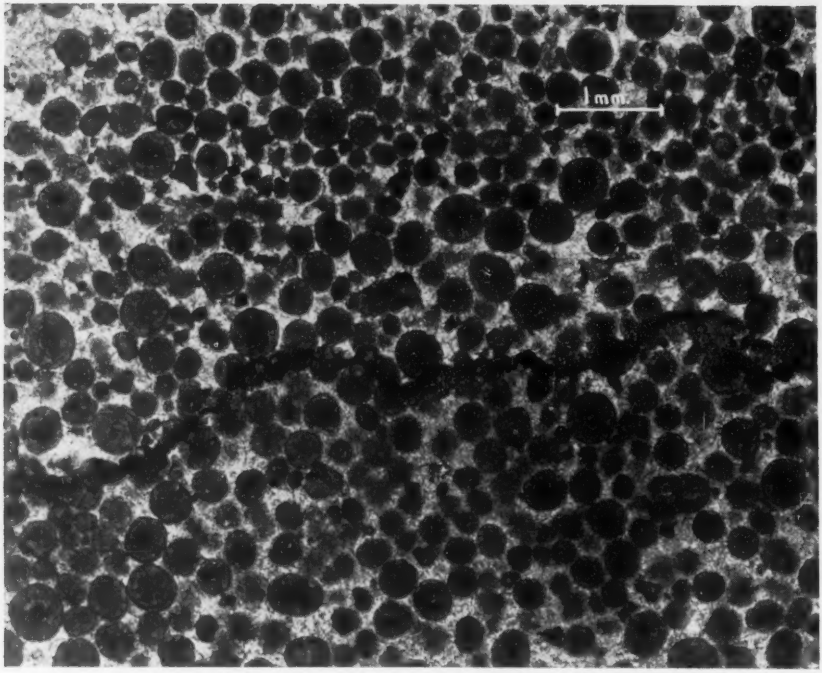


FIG. 5.—Stylolite with concentrated dolomite rhombs. Plain light.

Crystal faces of dolomite in the upper member of the Maurice Formation are unaltered. Thin section analysis of the mottled limestone indicated three different associations of oölites, dolomite rhombs and matrix. In each case, it appears that recrystallization of the calcite matrix, and hence lithification, preceded dolomitization. Field relations clearly indicated that dolomitization preceded regional fracturing of the rock.

Investigation of the possible origin of dolomite revealed that Early Paleozoic dolomites are more common than Late Paleozoic, Mesozoic, and Cenozoic dolomites. Recent studies by Chilingar (1956) indicated a progressive increase in the Ca/Mg ratio in limestones and dolomites since Precambrian time. Possible explanations of this relation include (1) difference in composition of Early Paleozoic marine waters, (2) increasing probability of a carbonate rock becoming dolomitized with time and (3) higher CO_2 pressure in the atmosphere during Precambrian and Paleozoic time. Limited data are available which suggest that the first of these hypotheses may have some substance.

Chemical analyses of metamorphic rocks (Clarke, 1924, p. 603, 617, 619, 621, 626) indicated the predominance of MgO over CaO (weight percent), as is shown in table 1.

According to Pettijohn (1949, p. 82), 77 to 84 percent of the metasedimentary schists analyzed by Bastin had an excess of

TABLE 1.—*Analyses of metamorphic rocks*

8 amphibolites	CaO greater than MgO
8 talc schists	MgO/CaO 3:1 to 50:1
4 quartzites and quartz schists	MgO/CaO 1:1 to 3:1
2 ferruginous schists	MgO/CaO 2:1
6 mica schists	MgO/CaO 2:1 to 30:1
7 gneisses	MgO/CaO approx. 1:1

TABLE 2.—*Analyses of sedimentary rocks*

	Average % MgO	Average % CaO
51 Paleozoic shales	2.32	1.41
27 Mesozoic and Cenozoic shales	2.67	5.96

magnesia over lime, as against only 8 percent of the acid igneous rocks and 35 percent of the basic igneous rocks.

Source areas for Cambrian sediments in the Western Interior consisted chiefly of Precambrian metamorphic rocks. Eckelmann and Poldervaart (1955, p. 1552) have demonstrated that at least some of the Precambrian basement in the Beartooth Range consists of metasediments. It seems logical to conclude, in terms of source area terrane, that Early Paleozoic sediments should be richer in MgO than CaO. Data presented by Clarke (1924, p. 552) lend credence to this hypothesis (table 2).

The formation of oölites requires shallow, continually agitated water (Krumbein and Sloss, 1951, p. 139). This precludes accumulation of muds in the strict sense. The resulting sediment consists of a well-sorted oölite sand with some finer-grained calcarenite matrix. Recent sediment studies on the Bahama banks indicated that areas of oölite sand and areas of carbonate mud are separated with rather sharp demarcation (Newell and Rigby, 1957, p. 54–55). Absence of interstitial clay gives oölitic sands a high primary porosity and permeability. Effective porosity trends would be oriented roughly parallel to bedding rather than vertically through the sediment, and would be a function of minor variations in sorting and packing of the finer calcarenite matrix surrounding the oölites. Secondary recrystallization of the calcarenite matrix should have preferential orientation parallel to bedding in terms of effective porosity due to initial sorting and pH and Eh trends resulting from interbedded organic material.

Following Late Cambrian sedimentation, the upper member of the Maurice Formation constituted a large, porous, permeable, tongue-like deposit of calcarenite surrounded by argillaceous sediments. Compaction of the underlying and overlying muds caused magnesia-rich connate waters to pass into and through the permeable oölite sands of the Maurice Formation. Solution migration and subsequent dolomitization of the upper Maurice calcarenite member was probably controlled by effective porosity trends subparallel to bedding.

Van Tuyl (1916, p. 345) concluded that all cases of mottling in limestones seem best explained on the assumption that magnesia was introduced into the formation from external sources. Beales (1953, p. 2290) noted that variability of dolomitic mottling in the Devonian Palliser limestone of Alberta resulted from effective porosity control rather than original composition of the rock. Osmond (1956, p. 40) studied mottling of the Simonson Formation in eastern Nevada and concluded that "development of the mottled pattern is the result of incomplete or differential dolomitization which may follow a pattern established at the time of deposition."

As indicated earlier, three different associations of oölites, dolomite rhombs, and matrix occur in the rock. In each of these, recrystallization of the matrix appears to have preceded dolomitization. The zones of tightly packed oölites in the finely crystalline calcite matrix are roughly parallel to bedding, and due to low effective porosity resisted dolomitization. The coarser clear crystalline calcite zone with scattered, partly dolomitized oölites, probably represents a more porous and permeable zone of coarse calcarenite with hydraulically equivalent oölites. Following recrystallization, the course calcite matrix had sufficiently low permeability to resist later dolomitization, though not to the same degree as the areas of tightly packed oölites in the finer matrix.

In areas of incipient dolomitization, oölites generally have dolomite rhombs concentrated in their nuclei. Gilbert (1954, p. 344) indicated that Recent calcareous oölites are predominantly composed of metastable aragonite. The conversion of aragonite to calcite is a slow process under normal conditions (Gilbert, 1954, p. 340–341). If protected by a covering of stable calcite, as in the shell structure of living Mollusca, aragonite will not convert to calcite.

It is suggested that during recrystalliza-

tion of the calcarenite matrix the periphery of the aragonitic oölites was converted to calcite. When this protective layer was formed, the aragonite in the centers of the oölites remained unaltered until the oölites were fractured during compaction. The metastable aragonite material in the nuclei of the oölites then constituted natural foci for dolomitization.

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ANALYTICAL PROCEDURES APPLICABLE TO FINE-GRAINED SEDIMENTARY ROCKS[1]

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ABSTRACT

Methods are described for the determination of major and minor chemical constituents in fine-grained sedimentary rocks. They include wet-chemical methods, radiometric and flame-photometric methods, absorption and emission spectroscopic methods, and fluorescent X-ray procedures. The major elements are determined by a rapid semi-micromethod on two samples, one of which is decomposed by fusion with sodium carbonate; the other sample is decomposed by digestion with sulfuric and hydrofluoric acids. Trace elements are determined by spectrochemical procedures using internal standards. Carbon, sulfur, and the carbon present in carbonate minerals are determined by conventional methods.

A fluorescent X-ray spectroscopic method for iron and molybdenum is described.

INTRODUCTION

This paper is the result of five years of analytical work on shales and lignites. Although the main purpose of the work undertaken in this laboratory has been an extensive mineralogical investigation of uraniferous shales and lignites, the methods described also have been used to analyze clays, limestones, sandstones, phosphates, and various relatively pure minerals. To date, the analysis of 1500 shale and 500 lignite samples has been completed.

The need for more rapid methods of analysis in the present-day investigation of geochemical and mineralogical problems has been emphasized by Shapiro and Brannock (1956), Corey and Jackson (1953), Hedin (1947), and many others.

The analysis of lignites and bituminous shales is complicated by several disturbing factors. Elements that are encountered in trace amounts in ordinary silicate rocks are often major constituents in lignites; the high organic content of bituminous shales and lignites requires that dry- or wet-ashing techniques be used; and the hygroscopicity of the lignites must be borne in mind.

Corey and Jackson (1953) devised a rapid semi-micromethod of analyzing silicate rocks which promised, with modifications, to be applicable to lignites as well. Using their paper as a starting point, a satisfactory scheme of analysis has been developed that can be used for a wide variety of sedimentary rocks.

The methods developed are simple, flexible, and can be mastered by personnel who have had little laboratory training. They are a great deal faster than conventional quantitative procedures and result in a higher degree of precision than is possible with classical methods which require highly skilled analysts to achieve reliable results.

The methods described have been checked by standard gravimetric and volumetric procedures and have proved to be comparable to those procedures in terms of accuracy and precision. Two National Bureau of Standards samples, plastic clay No. 98 and argillaceous limestone No. 1A, were analyzed by the methods described and the data are presented in table 1. As a further check,

TABLE 1.—*Analysis of bureau of standards samples*

Elements determined	Argillaceous limestone, no. 1A		Plastic clay, no. 98	
	Found	Reported	Found	Reported
SiO_2	14.2	14.1	59.3	59.1
Al_2O_3	4.22	4.16	25.2	25.5
Fe_2O_3	1.58	1.63	2.01	2.05
TiO_2	0.16	0.16	1.37	1.43
CaO	41.2	41.3	0.20	0.21
MgO	2.06	2.19	0.69	0.72
Na_2O	0.31	0.39	0.22	0.28
K_2O	0.69	0.71	3.20	3.17

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random samples were selected from the shales and lignites and determined by both standard and rapid methods. The results agree within ±2 percent. This is considered adequate for the problems under investigation in this laboratory.

Batches of ten samples are usually run at one time. The number depends, however, on the equipment available. If equipment is limited or if the analyst is inexperienced, it is best to do half that amount and carry one batch to completion before the next is begun. All samples should be run in duplicate and they can easily be carried to completion in two days.

A qualitative analysis of all new types of rocks, before the quantitative analysis is begun, is of the greatest importance. Using an emission spectrograph this requires little time and will give a good indication whether interfering elements are present in amounts that will seriously interfere. In many cases steps required to eliminate interfering elements may be omitted if these elements are known to be absent.

Although in actual practice it will be possible to carry on various steps of the complete analysis simultaneously, each procedure is described in such a way that it can be carried to completion before the next is undertaken.

APPARATUS AND INSTRUMENTS

The glassware and apparatus used are those commonly found in any well-equipped analytical laboratory. Whenever special equipment is required it will be noted under the specific method for which it is used.

A Beckman Model DU quartz spectrophotometer, equipped with a Beckman Model 4200 flame attachment and a Beckman Model 4300 photo-multiplier attachment, is used for all absorption and flame measurements.

The analysis of trace elements is done with a Jarrell-Ash Wadsworth grating spectrograph, Model JA-70. The density of the spectral lines is measured with an Applied Research Laboratories Comparator-Densitometer. The fluorescence measurements, in the analysis of uranium, are made with a Galvanek-Morrison reflectance type fluorimeter, Model JA-2600, manufactured by Jarrell-Ash Company, Newtonville, Massachusetts. Fluroescent X-ray spectroscopic determinations are made with a General Electric XRD-3 X-ray unit, lithium fluoride analyzer, tungsten target tube and fluorescence sample holder box.

All pH measurements are made with a Beckman pH meter, Model G, and glass electrode.

PREPARATION OF SAMPLES

Samples received from the field are ground to −100 mesh in large mullite mortars and placed in clean, dry glass jars. The covers are taped on with masking tape to prevent leakage and the glass jars are packed in sawdust in large pebble mill jars. The samples are then mixed on a rotating mill for 24 hours to give as homogeneous a mixture as possible. After mixing, the sample jars are removed, wiped free of any adhering dust, and stored until ready for use. Before weighing, the masking tape is removed from the covers; the jars once more are wiped free of dust with a clean cloth; and a portion of the sample required for analytical purposes is placed in a clean weighing bottle and dried to constant weight at 105° C.

Lignite samples are placed in desiccators over a solution of $CaCl_2 \cdot 6H_2O$ for 48 hours or until equilibrium with the moisture in the desiccator is reached. This makes it unnecessary to determine a moisture factor more than once during the analysis of the sample. Lignites have been found to be so extremely hydroscopic that changes in the humidity in the laboratory markedly affect the moisture content of the samples from day to day.

PREPARATION OF SAMPLE SOLUTIONS

Discussion

Two solutions are used for the analysis of the elements usually determined in sedimentary rocks. Aluminum, silicon, iron, titanium, calcium, and magnesium are determined on a 0.10–0.50 g sample that is decomposed by fusion with anhydrous sodium carbonate. Phosphorus, manganese, and the alkalies are determined on a 0.50 g sample that is decomposed by treatment with hydrofluoric, nitric, and sulfuric acids. Titanium, iron, and calcium could be determined on the sample decomposed with

acid; however, it is more convenient to use the sodium carbonate fused sample.

If the sample is a lignite or highly bituminous shale it is ashed before weighing to remove organic matter and concentrate elements such as titanium, manganese, phosphorus, etc. The sample used in the determination of the alkalies is ashed slowly at a temperature slightly below 450° C to prevent loss of sodium and potassium. Other types of sedimentary rocks may not need to be ashed, but should be dried to constant weight at 105° C before weighing.

Sodium Carbonate Fusion

Reagents—Reagent grade sodium carbonate, anhydrous.

Procedure.—Weigh 0.10–0.50 g of the ashed or dried sample into a 40-ml platinum crucible and intimately mix with 1–5 g of sodium carbonate. Cover the crucible with a platinum lid and place over a Meker burner. Heat, slowly at first, and finally with the full heat of the burner until the flux is melted. Two or three minutes from the time the flux melts is usually sufficient to decompose the sample. Remove the crucible from the flame and allow it to cool to room temperature. Add eight ml of 70% perchloric acid to the crucible which is kept covered with the platinum lid. Add the acid slowly (a drop at a time) or some of the sample may be lost through effervescence. After effervescence ceases, wash down the cover and sides of the crucible with water and allow the contents to digest on a low-temperature hot plate without boiling. When the sample is in solution, push the lid to one side of the crucible, and allow the contents to evaporate till dense fumes of perchloric acid are formed. When dense fumes appear, boil the contents of the crucible gently for a few minutes and take care to prevent spattering or baking. Allow the contents to cool and add 5 ml of distilled water and 5 ml of hydrochloric acid (1+1). Heat the crucible and contents until all soluble salts are in solution, cool, and transfer the contents to a pointed, graduated 50- or 60-ml centrifuge tube and make to the mark with distilled water. Stir the solution with an air-jet stirrer; rinse off the stirrer into the original platinum crucible. Set the crucible aside. Centrifuge the tube and contents at 1800 rpm for five minutes. Carefully remove a 40-ml aliquot of the supernatant liquid by pipette and transfer the contents to a dry 50- or 60-ml centrifuge tube for the determination of iron, titanium, calcium, and magnesium.

Hydrofluoric Acid Decomposition

Reagents.—Hydrofluoric acid, 48%; nitric acid, concentrated; sulfuric acid, 18N; sulfuric acid, concentrated.

Procedure.—Weigh 0.50 g of sample into a 50-ml platinum dish. Moisten the sample with a little water, add 0.8 ml. of 18 N sulfuric acid, 1 ml of concentrated nitric acid, and 10 ml of 48% hydrofluoric acid. Evaporate to fumes of sulfuric acid, cool, and add a few milliliters of water and 0.1 ml of concentrated sulfuric acid. Again evaporate to fumes of sulfuric acid. Cool, wash down the sides of the dish with about 5 ml of water, break up the crusts, and evaporate to fumes of sulfuric acid. Cool and dissolve the residue in 25 ml of hot water, boiling gently if necessary. Cool, transfer to a 100-ml volumetric flask, dilute with water and mix. This solution is used for the determination of potassium, sodium, phosphorus, and manganese.

METHODS OF DETERMINATION OF ELEMENTS

Silicon

In the determination of silicon (Hedin, 1947), the yellow silicomolybdate complex is developed following dehydration of the silica with perchloric acid (Williard and Cake, 1920). The percent light transmittance is read at 400 mμ. Since many lignite samples are quite high in phosphorus and arsenic, the removal of silica by dehydration affords a clean-cut separation from these before the complex is developed.

Apparatus and reagents.—Beckman Model DU spectrophotometer; 250-ml nickel beakers; 500-ml volumetric flasks; 50-ml volumetric flasks; 5% sodium hydroxide solution; sodium hydroxide pellets; ammonium molybdate solution prepared by dissolving 150 g of reagent grade ammonium molybdate in water and diluting to 1 liter and filtering if cloudy; hydrochloric acid (1+99); and hydrochloric acid (1+1).

Procedure.—After carefully withdrawing the remaining liquid from above the silica

in the centrifuge tube, add hydrochloric acid (1+99), mix with an air-jet stirrer and again centrifuge at 1800 rpm for 5 minutes. Withdraw as much of the wash liquid as possible without disturbing the residue and discard it. Wash the silica from the centrifuge tube into a 250-ml nickel beaker that contains about 2.5 g of reagent grade sodium hydroxide pellets, rinse out the tube and original platinum crucible with hot 5% sodium hydroxide solution, and finally police and rinse into the nickel beaker. Dilute the contents in the nickel beaker to 100 ml, heat to boiling, and boil gently for 5 minutes to dissolve the silica. Cool to room temperature, rinse into a 500-ml volumetric flask, dilute to volume and mix. Add 10 ml of ammonium molybdate solution to a 50-ml volumetric flask, dilute to about 30 ml with water, add 5 ml of hydrochloric acid (1+1) and swirl the mixture. Then, add 5 ml of the silica solution from the 500-ml flask, make to volume with water and mix. Allow the color to develop for one-half hour. Read the percent transmittance at 400 mμ. and calculate the percent silicon from a standard calibration curve previously constructed. Percent of silicon in the unknown can be computed:

$$\% \text{ Si} = \frac{\text{Micrograms Si per 50 ml.}}{\text{Aliquot} \times \text{Sample weight}} \times 100.$$

The standard curve is prepared by diluting 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 ml of a standard solution that contains 50 micrograms of silicon per ml of solution to 50 ml, and treating exactly as described for the development of the silicomolybdate complex in the test solution. The reference blank is prepared by adding 10 ml of ammonium molybdate solution to a 50-ml volumetric flask, diluting to 30 ml with water, adding 5 ml of hydrochloric acid (1+1), diluting to 50 ml with water and mixing.

Calcium

Calcium is determined in the presence of magnesium following the precipitation of iron, titanium, aluminum, etc. with ammonium hydroxide (Schwarzenbach and Biederman, 1948). A new indicator prepared by Patton and Reeder (1956) is used which changes from wine-red to clear blue when calcium is titrated with disodium EDTA (disodium dihydrogen ethylene diamine tetra-acetic acid) at a pH between 12 and 14.

Apparatus and reagents.—Bromcresol purple indicator; concentrated ammonium hydroxide (1+4); nitric acid; 8 N sodium hydroxide; standard calcium chloride solution exactly 0.01 N; 0.01 N disodium EDTA which is standardized against the 0.01 N calcium chloride solution; 2-hydroxy-1-(2-hydroxy-4-sulfo-1-Naphthylazo)-3- Naphthoic acid indicator which may be prepared as described by Patton and Reeder (1956) or obtained ready to use from Scientific Service Laboratories, P.O. Box 175, Dallas 21, Texas.

Procedure.—To the 40 ml of solution reserved for the determination of iron, aluminum, titanium, calcium, and calcium plus magnesium, add 3 drops of bromcresol purple indicator. Add concentrated ammonium hydroxide from a buret (drop by drop), stir with an air-jet stirrer until a precipitate begins to form; then add ammonium hydroxide (1+4) until the color of the indicator just turns from yellow to purple. Allow contents of the tube to cool, adjust with water to exactly 50 ml, mix, and heat in a water bath for 5 minutes; then cool the tube and contents. Centrifuge at 1800 rpm for 5 minutes. Pipette off two 20-ml portions carefully and place in 250-ml beakers for the determination of calcium and calcium plus magnesium.

Evaporate the 20 ml of solution reserved for calcium to dryness with 10 ml of concentrated nitric acid used to remove ammonium salts. A second evaporation with 2 or 3 ml of nitric acid, after washing down the sides of the beaker with water, is almost always necessary. Add to the cooled residue 1 ml of hydrochloric acid (1+1) and 50 ml of water. Neutralize the calcium solution with 8 N sodium hydroxide solution and add 4 ml in excess. Allow to stand 5 minutes, add 30 mg of sodium cyanide and 30 mg of hydroxylamine hydrochloride. Swirl mixture to dissolve the salts, add 0.1 g of calcium indicator and titrate with 0.010 N disodium EDTA to a clear blue end point. The percentage calcium can be calculated from:

$$\% \text{ Ca} = \frac{\text{ml. EDTA} \times \text{Normality of EDTA} \times 0.02004}{\text{Aliquot} \times \text{Sample weight}} \times 100$$

Each milliliter of exactly 0.0100 disodium EDTA solution is equivalent to 0.2004 mg of calcium.

As little as 0.10 per cent of calcium has been determined by this method. For best results, when small amounts of calcium are present, a microburet, graduated to 0.01-ml, is used.

Magnesium

Magnesium is determined as described by Corey and Jackson (1953), and by Schwarzenbach and others (1948). Titration with disodium EDTA is a measure of the total calcium plus magnesium in the solution; magnesium is then calculated by difference.

Reagents.—Ammonium hydroxide; 0.0100 N disodium EDTA solution; Eriochrome black T indicator solution (0.5 g of Eriochrome black T mixed with 4.5 g of hydroxylamine hydrochloride and dissolved in 100 ml of absolute methyl alcohol); sodium cyanide; hydroxylamine hydrochloride.

Procedure.—To the aliquot reserved for the determination of total calcium plus magnesium add 5 ml of concentrated ammonium hydroxide and dilute to 50 ml with distilled water. Add 30 mg each of sodium cyanide and hydroxylamine hydrochloride and stir to dissolve. Add 5 drops of Eriochrome black T indicator solution and immediately titrate to a clear blue end point with 0.0100 N disodium EDTA, using a blank for comparison.

The percentage magnesium in the sample can be calculated by subtracting the amount of 0.0100 N disodium EDTA required to titrate the calcium solution from that required for total calcium plus magnesium. Thus, percentage of magnesium in the sample = (ml of EDTA required for total calcium plus magnesium) − (ml of EDTA required for calcium) × normality of disodium EDTA × 0.01216 × 100/aliquot × sample weight. If the aliquot taken for the determination of calcium differs from that taken for total calcium plus magnesium, the percentage of magnesium in the sample can be calculated by subtracting the milliequivalents of calcium per gram from the milliequivalents of calcium plus magnesium per gram and multiplying by 1.216.

Aluminum

Aluminum is determined by the aluminon method of Smith, Sager, and Siewers (1949) after it is separated from iron and titanium, with concentrated sodium hydroixde solution as the aluminate ion.

Apparatus and reagents.—Buffer solution, pH 4.2 (60 ml of glacial acetic acid diluted to 900 ml, to which a 100-ml portion of 10% sodium hydroxide solution is added. Adjust the pH to 4.2 with a pH meter by adding small portions of 10% sodium hydroxide); aluminon reagent (exactly 0.200 g of aluminon is dissolved in 100 ml of pH 4.2 buffer solution and diluted to 500 ml with water). Standard aluminum solution containing 5 micrograms of aluminum per ml of solution (prepared by dissolving 0.08795 g of $KAl(SO_4)_2 \cdot 12H_2O$ in a liter of water and standardizing by precipitating the aluminum with ammonium hydroxide, igniting, and weighing as Al_2O_3); 1% ammonium chloride solution; 5% ammonium carbonate solution; sodium hydroxide solution (made by dissolving 25 g of sodium hydroxide in 100 ml of water).

Procedure.—The treatment of the precipitated hydroxy oxides of iron, titanium, and aluminum now depends on the presence in the sample of uranium and also on the percentage of iron present. Uranium interferes in the determination of iron and titanium with Tiron, and aluminum tends to be adsorbed or co-precipitated on the iron precipitate when sodium hydroxide is added. Therefore, if much uranium is present, it is best removed in the next step.

1. If uranium is present wash the hydroxides in the centrifuge tube with 20 ml of 5% ammonium carbonate solution, stir with the air-jet stirrer, dilute to 50 ml with water and again stir. Centrifuge at 1800 rpm for 5 minutes and withdraw the supernatant liquid which contains the uranium. Wash again with a 1% solution of ammonium chloride, mix, centrifuge, and withdraw and discard the ammonium chloride solution.

2. If uranium is not present wash the hydroxides only once with 1% ammonium chloride and omit the treatment with ammonium carbonate.

To the precipitate in the centrifuge tube add 3 ml of hot hydrochloric acid (1+1). The succeeding steps depend on the amount of iron present. If the iron does not exceed 5 percent, add 10 ml of hot sodium hydroxide solution. Stir the solution and heat the tube

in a hot water bath for 5 minutes. Cool, dilute to 50 ml with water, mix well, and centrifuge for 5 minutes at 1800 rpm. Pipette five milliliters of the supernatant liquid into a 100-ml volumetric flask and add 3 ml of hydrochloric acid (1+1). Dilute the solution to 100 ml with water, mix, and reserve for the determination of aluminum.

If the iron exceeds 5 percent, provision must be made to prevent the coprecipitation of aluminum. This is most easily accomplished as follows. To the dissolved hydroxides in hydrochloric acid add enough 8 N sodium hydroxide to neutralize the solution and then add 2 ml in excess (Snell and Snell, 1949). Mix and add 10 ml of 8 N sodium hydroxide solution saturated with hydrogen sulfide, mix and heat in a hot water bath for 5 minutes. Cool, dilute to 50 ml, mix and centrifuge at 1800 rpm, then pipet 5 ml of the supernatant liquid into a 100-ml volumetric flask, add 3 ml of hydrochloric acid (1+1), dilute to the mark with water and mix, reserve for the determination of aluminum. Withdraw the remaining liquid by gentle suction and discard it. Dissolve the precipitate of iron and titanium in 1 ml of hydrochloric acid (1+1) and then transfer to a 100-ml volumetric flask, add a drop of 3% hydrogen peroxide, dilute the solution with water, mix and set aside for the determination of iron and titanium.

For the determination of aluminum add 10 ml of pH 4.2 buffer solution to a 50-ml flask and add 20 ml of water. Then add 10 ml of 0.04% aluminon reagent and swirl the mixture, add 5 ml of the test solution previously reserved for aluminum (a 5-ml aliquot should be suitable for samples containing 1 to 8 percent of aluminum). Dilute with water to 50 ml, mix, and allow the color to develop for one-half hour. Read the percent transmittance at 520 mμ against a reference blank that contains exactly the same amount of reagents as the test solution. Control of pH, temperature, and time for color development must be strictly adhered to in order to secure good reproducibility. From the standard aluminum curve (prepared by taking 1, 2, 3, 4, 5, 6, 7, and 8 ml of the stock aluminum solution and treating as above) the percentage aluminum in the sample may be calculated:

$$\% \text{ Al} = \frac{\text{micrograms Al per 50 ml}}{\text{Aliquot} \times \text{sample weight}} \times 100.$$

Iron

Total iron is determined with Tiron (Yoe and Jones, 1944). The blue color developed below pH 5.0 is read at 565 mμ. $MoO_4^{=}$, $OsO_5^{=}$, Cu^{++}, UO_2^{++}, VO^{+}, and Ti^{++++} interfere. However in the procedure as outlined $MoO_4^{=}$, UO_2^{++}, VO^{+} and Cu^{++} are removed and Ti^{++++} does not interfere at the wavelength used. $OsO_5^{=}$ is not likely to be present.

Apparatus and reagents.—Disodium-1, 2-dihydroxybenzene-3, 5-disulfonate (Tiron, the LaMotte Chemical Products Co., Chestertown, Md.); buffer solution, pH 4.7 (equal volumes of 1M acetic acid and 1M sodium acetate); 3% hydrogen peroxide; hydrochloric acid; standard iron solution that contains 50 micrograms of iron per milliliter.

Procedure.—Pipet 10 ml of pH 4.7 buffer solution into a 50-ml volumetric flask, add 20 ml of water and 5 ml of 4% Tiron solution. Add an aliquot from the solution prepared for the determination of iron and titanium in the 100-ml flask that will contain from 50 to 250 micrograms of iron. The dilution will depend on the percentage iron in the sample. Dilute to 50 ml with water, mix, and read the percent transmittance at 565 mμ. From the standard iron curve (prepared by taking 1, 2, 3, 4, 5, 6, 7, and 8 ml of the stock iron solution and treating as above) the micrograms of iron in 50 ml can be obtained, and the percentage iron in the sample can be calculated:

$$\% \text{ Fe} = \frac{\text{micrograms Fe per 50 ml}}{\text{Aliquot} \times \text{Sample weight}} \times 100.$$

Titanium

Titanium is determined with Tiron (Yoe and Armstrong, 1947) after the reduction of the iron with solid sodium dithionite. A slight turbidity may develop after 20 minutes; therefore, the samples should be read as soon as possible. Mo, V, W, U, and Bi would interfere but they are removed in the procedure.

Apparatus and reagents.—Tiron; pH 4.7 buffer solution prepared as directed under iron; 3% hydrogen peroxide; sodium dithi-

onite; standard titanium solution that contains 10 micrograms of titanium per ml.

Procedure.—Pipet 10 ml of pH 4.7 buffer solution into a 50-ml volumetric flask, add 20 ml of water and 5 ml of 4% Tiron (4 g Tiron diluted with water to 100 ml). Add an aliquot from the iron and titanium solution that will contain from 10 to 100 micrograms of titanium. Add 3 to 5 mg of solid sodium dithionite. Dilute to 50 ml with water and carefully mix without excessive shaking until the blue iron color is destroyed and the yellow titanium complex is developed (approximately 10 minutes). The percent transmittance is read at 400 mμ and the amount of titanium in the 50 ml is obtained from a standard titanium curve prepared by taking 1, 2, 3, 4, 5, 6, 7, and 8 ml of the stock titanium solution and treating as above. The percentage titanium in the sample is then calculated:

$$\% \text{ Ti} = \frac{\text{micrograms Ti per 50 ml}}{\text{Aliquot} \times \text{Sample weight}} \times 100.$$

Sodium, Potassium and Lithium

After the separation of the oxides and calcium, the alkalies, lithium, potassium, and sodium, are determined by a flame photometer method (Horstman, 1956). Rubidium and cesium can be determined on the same sample if desired.

Apparatus and reagents.—Beckman Model DU spectrophotometer with Beckman Model 4200 photomultiplier attachment and Beckman Model 4200 flame attachment; oxygen and acetylene gas; standard potassium, sodium, and lithium solutions; calcium carbonate, low in alkalies; 95% ethyl alcohol; bromothymol blue indicator solution.

Procedure.—From the solution prepared as described under "Hydrofluoric Acid Decomposition," pipet into a Pyrex beaker an aliquot that will contain 0 to 100 micrograms of the alkalies. Dilute to 75 ml with distilled water, and add 5 drops of bromothymol blue indicator. Carefully neutralize the solution with solid calcium carbonate. Do not add more than enough of the calcium carbonate to just change the color of the indicator from yellow to blue. If the color does not change to blue on the addition of 0.5 to 1.0 g, set the beaker on the steam bath and warm for an hour or so. Usually this will suffice, if it does not add a little more calcium carbonate. When the pH is between 7.6 and 7.8 allow the precipitate to age overnight, heat to boiling, and filter on an 11-cm medium grade filter paper. Wash with hot water until the volume of the filtrate and washings is 150 ml. Evaporate to 50 ml, cool, and add 50 ml of 95% ethyl alcohol. Set aside overnight, filter through an 11-cm medium grade filter paper, and wash with 50 percent ethyl alcohol. Evaporate the solution to dryness, add hot water to dissolve the residue, transfer to a 50-ml volumetric flask, dilute to volume, and mix. A blank should be carried through all the steps of the procedure.

If the samples cannot be read at once transfer the solutions to polyethylene bottles, seal tightly, and keep until ready for use.

Using spectrographically analyzed sodium chloride, potassium chloride, and lithium chloride, prepare standard solutions containing 100 micrograms of each alkali per milliliter of solution. Dilute these, mix together to obtain standards for the range of either 0 to 10 micrograms or 10 to 100 micrograms of potassium, sodium, and lithium per milliliter of solution. The flame photometer is standardized for the range 0 to 10 micrograms or 10 to 100 micrograms of sodium per milliliter of solution, depending on the concentration of sodium in the test solution. Obtain galvonometer reading for the unknown solution and the concentration of sodium from a standard curve. Then, in turn, standardize the flame photometer for potassium and lithium. Repeat the same procedure for the potassium and lithium determinations. Potassium is read at 766 mμ, sodium at 589 mμ, and lithium at 671 mμ. The percentage of each alkali in the sample may be determined:

$$\% \text{ alkali} = \frac{\text{micrograms alkali} \times 50}{\text{Aliquot} \times \text{Sample weight}} \times 100.$$

Phosphorus

Phosphorus is determined by measuring the light transmitted by a solution at 430 mμ following the development of the yellow molybdivanado-phosphoric acid complex (Kitson and Mellon, 1944).

Reagents.—Standard phosphorus solution (0.2132 g of ammonium monohydrogen phosphate dissolved in water and diluted to 1 liter. Each ml will contain 0.05 mg of phosphorus per ml); molybdivanadate solution (1.25 g of ammonium metavanadate dissolved in 400 ml of nitric acid (1+1), 50 g of ammonium molybdate dissolved in 400 ml of water. Mix the two solutions and dilute to 1 liter with water).

Procedure.—From the solution prepared for the determination of the alkalies, phosphorus, and manganese, pipet into a 50-ml volumetric flask an aliquot containing from 1 to 50 ppm phosphorus. Add 10 ml of molybdivanadate solution and swirl. Add water to bring to the mark, mix, and allow to stand for 5 minutes. Read the percent transmittance at 430 mμ, and from the standard curve determine the micrograms of phosphorus per 50 ml. The standard curve is prepared by pipetting into a 50-ml volumetric flask 1, 2, 3, 4, 5, 6, 7, and 8 ml of the standard stock solution that contains 50 micrograms of phosphorus per ml and by developing the yellow molybdivanadophosphoric acid complex as described above. The percent of phosphorus in the sample may then be calculated:

$$\% \text{ P} = \frac{\text{micrograms P per 50 ml}}{\text{Aliquot} \times \text{Sample weight}} \times 100.$$

Manganese

Manganese content is determined by the method of Willard and Greathouse (1917). The manganese is oxidized to permanganate with KIO_4, and the percent of light transmitted by the solution is measured at 525 mμ or 545 mμ if chromate is present.

Reagents.—Standard manganese solution (0.2877 g of $KMnO_4$ dissolved in water and diluted to 1 liter. Each ml should contain 0.1 mg of manganese, but the solution should be standardized before using). From this standard manganese solution, prepare a stock solution that will contain 50 micrograms of manganese per ml. Reagent grade KIO_4; 100 ml of phosphoric acid and 500 ml of sulfuric acid, mixed, and diluted to 1 liter.

Procedure.—From the solution prepared for the determination of the alkalies, phosphorus, and manganese, pipette into a 50-ml volumetric flask an aliquot containing from 1 to 15 ppm manganese. Add 25 ml of the phosphoric-sulfuric acid solution and mix. Then add 0.1 g of solid KIO_4 and heat near the boiling point in a water bath for 15 minutes. Cool, dilute to volume, and mix. Read the percent transmittance at 525 mμ and determine the micrograms of manganese per 50 ml from a standard curve. The percentage manganese in the sample may be calculated:

$$\% \text{ Mn} = \frac{\text{micrograms Mn per 50 ml}}{\text{Aliquot} \times \text{Sample weight}} \times 100.$$

Carbon and Hydrogen

Total carbon and hydrogen in bituminous shales and lignites are determined by a rapid technique first described by Millin (1939) and modified by Grace and Gauger (1946). Because many of the rocks analyzed contain carbonate minerals, a temperature of 900°–950° C and a longer combustion time than that recommended in the original paper are maintained.

Apparatus and reagents.—An organic combustion apparatus consisting of 3 heating units; needle valve and gauge attached to a supply tank of oxygen; flow meter; fused quartz combustion tube (Amersil Company, Inc., Hillside 5, New Jersey); Nesbitt tube filled with anhydrone; Nesbitt tube filled with caroxite; fused lead chromate pellets; silver ribbon turnings (T. B. Hagstoz & Son, Philadelphia, Pa.); copper oxide; oxidized copper screen plugs; combustion boats.

Procedure.—Pack the combustion tube as described by Grace and Gauger; use only a few pellets of lead chromate in place of the 25 cm recommended. This greatly lengthens the life of the tube. A preheating furnace has been found unnecessary and is not used.

Test the combustion train at operating temperature until blanks indicate that there is a change in the weight of the Nesbitt absorption tubes of no more than 0.5 mg. Connect the absorption tubes to the train, insert the combustion boat containing the sample (not less than 0.2–0.3 g) into the tube and move to the clear section; follow by the copper oxide wire spiral. The 13-cm furnace which is at the extreme end of the stand should be at about 500°C. Adjust the oxygen flow so that the rate of flow is 100

ml per minute, set the rheostat on the 13-cm furnace for 900°–950° C and allow the unit to reach that temperature, which it does in a few minutes. Slowly move the furnace up to the boat so that at the end of ten minutes it is against the 33-cm furnace which is at a temperature of 900° C. After five minutes move both furnaces back to the extreme end of the stand. Then, adjust the rheostat on the 13-cm furnace to 500° C and after ten minutes return the 33-cm furnace to its original position. Maintain the flow of oxygen for five more minutes, shut the absorption tubes off under pressure and cut off the flow of oxygen. Remove the absorption tubes from the train, allow to come to the balance temperature, vent, wipe with a clean dry cloth and weigh. The percent of carbon may be calculated:

$$\% \text{ C} = \frac{\text{weight } CO_2 \times 27.29}{\text{weight of sample}}.$$

The percent of hydrogen may also be calculated:

$$\% \text{ H} = \frac{\text{weight } H_2O \times 11.19}{\text{weight of sample}}.$$

Non-essential Water

If the determination of hygroscopic water (H_2O^-) is also desired, it can best be determined by drying 1.0 g of the sample to constant weight in a weighing bottle at 105° C. Because of the hygroscopic nature of highly bituminous shales, it is best to weigh samples of the air-dried material for analysis and determine the hygroscopic water on a separate portion. If a complete summation is not required, the samples are best dried for two hours at 105° C in a weighing bottle, cooled in a desiccator, and weighed at once.

Lignite samples are so hygroscopic that a special technique for handling was adopted. All samples were kept in uncovered weighing bottles in a desiccator over $CaCl_2 \cdot 6H_2O$ for at least forty-eight hours. A moisture factor was determined on each set of samples by drying 1.0 g of sample at 105° C to constant weight. The samples were kept in the desiccator until all determinations were made. Experiments conducted over a number of years have shown that this gives a higher degree of reproducibility, without the need of determining a moisture factor each time a sample is weighed. The hygroscopicity of the lignites is so great that air dried samples gain weight even during the actual time required for weighing, but samples kept as described above were not affected. The percent of moisture was calculated as follows:

$$\% \text{ M} = \frac{\text{Weight loss}}{\text{Weight sample}} \times 100$$

Ash

The percent of ash, and loss on ignition if desired, may be determined for lignites in two ways:

1. If the percent ash is required as a factor or if it is desirable to ash enough sample for the determination of the invola-tile elements, the determination is begun by weighing 20.0 g of the raw lignite into a flat, fused quartz dish and slowly igniting in a muffle furnace. The temperature is raised slowly to 450° C and kept at this temperature until most of the combustible material has disappeared, care being taken that the heating is gradual enough to prevent deflagration. The temperature is then raised to 750° C, the ash ignited at 750° C for one hour, cooled in a desiccator, and weighed. The ignition at 750° C is repeated until constant weight is obtained.

2. Samples that are to be used for the determination of volatile elements are weighed into flat, fused quartz dishes and heated for 1 hour at 150° C; the temperature of the samples is then raised to 225° C and maintained there for one hour. Then, the temperature of the samples is slowly increased to 450° C and the sample is ignited at this temperature for five hours. After cooling, the samples are weighed and re-ignited at 450° C until constant weight is obtained. The percent of ash may then be calculated:

$$\% \text{ Ash} = 100 - \% \text{ L.O.I.}$$

Total Sulfur

Total sulfur is determined most easily in bituminous shales and lignites by using the procedure described by Stanton, Fieldner, and Selvig (1938).

Apparatus and reagents.—Eschka mixture (2 parts calcined MgO, 1 part anhydrous

Na_2CO_3); bromine water; hydrochloric acid (1+1); methyl orange indicator; 10% barium chloride solution.

Procedure.—Mix 1.0 g of the sample with 3 g of Eschka mixture in a large porcelain or platinum crucible. Cover the mixture with 1 g of Eschka mixture and heat slowly in an electric muffle furnace. When the temperature reaches 450° C maintain at this temperature for one-half hour, then increase the temperature to 800° C, and ignite at 800° C for one hour. If on cooling there is any evidence of organic matter present, as shown by black particles in the mixture, repeat the ignition at 800° C until all organic matter has burned away.

Transfer the cooled mixture to a 250-ml beaker with hot water and heat for 30 minutes in about 100 ml of water. Filter onto an 11-cm medium grade filter paper, wash the residue with hot water until the volume of the filtrate and washings is about 250 ml, add 5 ml of bromine water and enough hydrochloric acid to make the solution slightly acid. Boil until all of the bromine has been expelled, add 3 drops of methyl orange indicator, and adjust the pH with dilute ammonium hydroxide so that the color of the indicator just turns from yellow to pink when 1 drop of dilute hydrochloric acid (1+4) is added. Heat to boiling and slowly add, while stirring constantly, 10 ml of a 10% barium chloride solution. Allow the precipitate to stand for several hours. Filter on an 11-cm fine grade filter paper, wash with hot water until the wash liquid shows no turbidity when tested with a 1% solution of silver nitrate. Ignite the paper and residue in a porcelain or platinum crucible, slowly at first until the paper has charred, and finally at 900° C. Cool, weigh, and again ignite and weigh until constant weight is attained. The percent of sulfur in the sample may be calculated:

$$\% \text{ S} = \frac{\text{weight of } BaSO_4}{\text{weight of sample}} \times 13.74$$

Carbon in Carbonate Mineral

If it is necessary to determine the carbon present as carbonate, several methods may be found in the literature. The method selected will depend on several factors: the accuracy and precision required, the rock type, the time available for analysis, etc. Except for the method proposed by Shapiro and Brannock (1956), the author knows of no rapid method. Unfortunately that method is not reliable if organic material is present or if the percent of CO_2 is much higher than one or two percent.

The method best suited to shales and lignites is the one described by Hillebrand and others (1955). In that method the carbon dioxide is liberated with hot dilute acid and is then absorbed in caroxite.

Apparatus and reagents.—Absorption train for carbon dioxide; hydrochloric acid (1+1) or orthophosphoric acid (1+4).

Procedure.—Carefully transfer from 1 to 5 g of the sample to the digestion flask. Connect the apparatus and sweep out the flask for 5 minutes with CO_2-free air. Connect the tubes filled with caroxite to the train, open the stopcocks and allow phosphoric acid (1+4) to run into the flask, slowly if there is much carbon dioxide, rapidly if there is little. Close the stopcock from the separatory funnel, start the water running through the condenser, and heat the contents of the flask until the solution has boiled gently for 3 to 5 minutes. Remove the heat gradually, open the stopcock from the separatory-funnel and sweep out the carbon dioxide in the flask with CO_2-free air. When it is judged that all the CO_2 generated has been swept out, close the stopcocks in the caroxite filled tube, remove from the train, and allow to cool near the balance. Vent the tube momentarily, wipe dry with a clean, dry cloth and weigh. The percent of carbon dioxide may then be calculated:

$$\% \ CO_2 = \frac{\text{weight of } CO_2}{\text{weight of sample}} \times 100$$

DETERMINATION OF IRON AND MOLYBDENUM BY FLUORESCENT X-RAY SPECTROSCOPY

Discussion

Wherever an instrument is available the X-ray fluorescence method is particularly suitable for the determination of iron and molybdenum.

Iron and molybdenum are determined with a precision of ± 2 percent. As many as 50 duplicate determinations can be finished in an eight-hour day by one technician.

Apparatus

General Electric XRD-3 X-ray unit, lithium fluoride analyzer, tungsten target tube, and fluorescence sample holder box. Sample holders made from $\frac{1}{8}$ in. sheet aluminum by machining a rectangular depression ($\frac{3}{4}$ in. by $\frac{1}{2}$ in. by 1/20 in.) into a plate of aluminum $1\frac{5}{8}$ in. by 2 in.

Iron

For the determination of iron the tube is operated at 50 Kv and 2 ma. The low amperage is necessary to keep the fluorescent X-ray intensity within counting rates that can be handled by the geiger tube for the total range (0.1 percent to nearly 60 percent iron). The low amperage gives a very low background intensity (about 1.5 counts per second).

Standards are prepared from ashed samples. The standard samples are analyzed for total iron by the classical volumetric method (i.e., digestion with hydrochloric acid, fluxing the insoluble residue with potassium pyrosulfate, reduction of the iron with stannous chloride, and titration with potassium dichromate). Each standard is analyzed four times in duplicate, and the average value of all eight analyses is used as the standard value.

The sample is packed into the aluminum sample holder by using a clean glass slide to pack and smooth the surface of the sample. The iron Kα peak at 57.50° 2θ (for LiF) and background at 60.0° 2θ are used. The number of seconds required to record a fixed number of counts is measured. Three readings are taken on each duplicate using a fixed count of either 16,384 or 8,192 counts depending on the iron content.

The working curve is plotted as counts per second against percent of iron.

Molybdenum

Procedure.—Molybdenum is determined using the same equipment as that used for the determination of iron. Samples are ashed to eliminate the hydration effects of the organic material and to concentrate the molybdenum. For the determination of molybdenum, the tube is operated at 50 KV and 50 ma. Intensities of the fluorescent X-rays are read at each of the following positions: Mo Kα at 20.30° 2θ, ULα at 26.14° 2θ, and background at 15.00° 2θ. Molybdenum has the highest characteristic radiation energy of any of the elements detected in the ash so it suffers no enhancement due to secondary fluorescence. A major interference, however, has been found in the Mo Kα peak due to the superposition of the ULβ peak. It was empirically determined that the latter peak has 15 percent of the intensity of the ULα peak. The ULα peak is therefore measured and 15 percent of its intensity subtracted from the combined intensities of the ULβ_3 and Mo Kα peaks; the intensities are determined by counting the number of seconds required to amass a predetermined number of counts. The final, corrected intensity for the molybdenum may then be computed:

$$I = [(I_{MoK\alpha} - I_\beta) - 0.15(I_{UL\alpha} - I_\beta)],$$

where

I = Corrected intensity

I_β = Intensity of background

$I_{MoK\alpha}$ = Intensity of molybdenum Kα peak

$I_{UL\alpha}$ = Intensity of uranium Lα peak

Ashed lignite samples were analyzed to obtain molybdenum values for the standard working curve. Those that contained less than 0.5 percent molybdenum were determined colorimetrically with mercaptoacetic acid (Will and Yoe, 1953); those that contained more than 0.5 percent molybdenum were determined by both the colorimetric method and by the gravimetric method with alpha-benzoinoxime (Knowles, 1932). The standard working curve was prepared by plotting percents of molybdenum against the corrected intensities.

FLUORIMETRIC ANALYSIS OF URANIUM

Uranium may be analyzed fluorimetrically as described by Grimaldi and Levine (1954, p. 43–48). The method depends on the extraction of uranyl nitrate from a 7% nitric acid solution into ethyl acetate using aluminum nitrate as a salting out agent.

Apparatus and reagents.—Galvanek-Morrison reflectance type fluorimeter, Model JA-2600; Gyrotory Shaker Model S3 (New Brunswick Scientific Company, New Brunswick, N. J.) on which an electric muffle furnace is mounted; stainless steel rack that

fits into the muffle furnace and is designed to hold eight platinum fluxing dishes; platinum dishes; ethyl acetate, reagent grade; aluminum nitrate enneahydrate, Baker's reagent grade; nitric acid (1+1); hydrofluoric acid, 48%; fluxing mixture: prepared by intimately mixing −80 mesh reagent grade Na_2CO_3 (45.5 g), reagent grade K_2CO_3 (45.5 g), and reagent grade NaF (9 g); volumetric flasks, 50-ml, or 50-ml stoppered graduated cylinders; stoppered test-tubes, 30-ml (Scientific Glass Apparatus Company, Inc., Bloomfield, N.J.); pipets, 10-ml, 5-ml, 1-ml (graduated to 0.1 ml).

Procedure.—Weigh 0.150 g of the sample into a flat-bottomed, platinum dish and ignite gently until all organic matter has burned away. Cool, add 5 ml of nitric acid (1+1) and 10 ml of hydrofluoric acid (48%), and evaporate to dryness. Cool, add nitric acid (1+1) and again evaporate to dryness. Repeat the evaporation with nitric acid once more. Add 7 ml of nitric acid (1+1) to the cooled residue and warm gently until all salts are dissolved. Cool and dilute with water in a 50-ml volumetric flask or graduated cylinder. Mix and transfer 5 ml of the solution to a 30-ml stoppered test-tube into which exactly 9.5 g of aluminum nitrate enneahydrate have been placed. Heat in a water bath until the aluminum nitrate is completely melted, cool to room temperature, and add exactly 10 ml of ethyl acetate. Shake the test tube for 1 minute, allow to stand for 1 or 2 minutes, and filter through a 9-cm filter paper into a small test tube. Take care to transfer only the ethyl acetate layer. Immediately pipet 0.8 ml of the filtered ethyl acetate into a flat platinum fluxing dish (May and Fletcher, 1954, p. 103). Burn off the ethyl acetate in a shallow pan lined with water-soaked paper napkins, heat gently on a small hotplate to remove any acetic acid, and add 2.0 g of carbonate-fluoride flux. Place the fluxing dishes in the stainless steel rack and transfer to the muffle furnace which has been preheated to 650° C. Allow the flux to just melt and then set the gyrotory shaker for 2 minutes (longer heating periods have been found unsatisfactory because of the solution of platinum in the melt). When the shaker stops, allow a few seconds for the melted flux to run down from the sides into the dish; remove the rack from the furnace being careful to keep the flux level in the dishes until the melt has solidified. As soon as the melt has crystallized, place the dishes on an asbestos board until cool and then transfer them to a desiccator. After 15 minutes, remove the pads containing the uranium from the platinum dishes and read the percent of fluorescence.

Melts containing known amounts of uranium and a blank may be used to establish a standard curve. From the standard curve, the micrograms of uranium in the unknown melt can be determined and the percent of uranium may be calculated:

$$\% \text{ U} = \frac{\text{Micrograms U in unknown melt}}{\text{Aliquot} \times \text{Sample weight}} \times 100$$

SPECTROCHEMICAL ANALYSIS OF TRACE ELEMENTS

The quantitative determination of trace elements in lignite ash, shales, and silicates is most easily accomplished as described by Ahrens (1955).

Synthetic standards may be used to prepare the emulsion calibration curves and the working curves. The major elements in shales, lignite ash, and silicate rocks are usually SiO_2, Fe_2O_3, Al_2O_3, CaO, MgO, K_2O, and Na_2O. Taking the average values of these elements as determined quantitatively for a large number of samples, synthetic standards may be carefully prepared from spectrographically analyzed reagents obtained from Jarrell-Ash Company, Newtonville 60, Massachusetts. A series of standards containing exactly 1.0, 0.5, 0.2, 0.1, 0.05, 0.02, 0.01, 0.005, 0.002, 0.001, 0.0005, and 0.0001 percent of the elements to be determined may then be prepared. These are used to prepare calibration and working curves.

As recommended by Ahrens, the elements should be divided into two groups. One group of elements, containing Ba, Co, B, Cr, Be, Mo, Mn, Ni, V, Sr and Zr, is referred to as the "involatile" group. The other, containing Pb, Ag, Cu, Zn, Sn, Bi, Ge, As, and Sb, is referred to as the "volatile" group.

The "involatile" elements may be analyzed by using palladium as the internal standard. A buffer mixture is prepared by mixing one part of palladium to one thousand parts of powdered carbon. Ten mg of this mixture is added to 5 mg of sample. Using the d-c arc with a current of 9.5–10 amperes and 120 seconds total burning time, the author found the best electrode to be $\frac{1}{4}$ in. HP graphite. Eight exposures and an iron reference exposure can be recorded on a 4-inch emulsion plate.

The "volatile" elements may be determined by using indium oxide as the internal standard. Two percent indium oxide is added to potassium sulfate, and one percent of this mixture is added to the sample. A $\frac{1}{4}$ in. HP graphite electrode is used with a current of 4–5 amperes and a total burning time of 30 seconds.

RESULTS AND DISCUSSION

The methods described have been tested by analyzing two National Bureau of Standards samples, one argillaceous limestone and one plastic clay. The results obtained are listed in table 1. These are the averages of four determinations.

To further test the precision that can be expected, the data obtained for the unknown samples analyzed were subjected to statistical analysis. The standard deviation of each element was calculated from

$$\sigma = \sqrt{\frac{\Sigma X^2 - \frac{(\Sigma X)^2}{n}}{n-1}}.$$

The results, in terms of percent of the determined value, were: silicon $\pm 1\%$, iron $\pm 2\%$, titanium $\pm 2\%$, aluminum $\pm 2\%$, calcium $\pm 1\%$, magnesium $\pm 3\%$, phosphorus $\pm 0.3\%$, uranium $\pm 2\%$, carbon $\pm 0.8\%$, sulfur $\pm 1\%$ and CO_2 $\pm 3\%$. In all but the lower concentration ranges the reproducibility was well within the limits reported.

All of the methods described have been applied successfully to the analysis of shales and lignites in this laboratory.

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FIGS. 1–5, JUNE, 1959

NOTES

COLUMNAR CONTEMPORANEOUS DEFORMATION[1]

CLYDE T. HARDY AND J. STEWART WILLIAMS
Utah State University, Logan, Utah

Small-scale columnar structures (fig. 1), due to contemporaneous deformation, are remarkably well-formed at one known locality in the Ute Formation of Cambrian age in the Wasatch Range of northern Utah. The exposure is about 5 miles north of Brigham City, Utah, on the northern side of a canyon which dissects the exceedingly steep western front of the Wasatch Range. An abandoned concrete building may be seen in this canyon from the highway north of Brigham City; the columnar structures are readily accessible near a mine dump a short distance beyond the building. The Ute Formation, on the northern side of the canyon, is separated from the Brigham quartzite and overlying Langston Formation, on the southern side, by a high-angle fault which trends east-northeast.

The best-formed columns occur in two stratigraphic intervals of interbedded, thin-bedded, gray limestone and brown-weathering, silty limestone. The upper interval, just west of the mine dump, is about 5 ft thick. It may be seen at places for a considerable distance westward to the mountain front and also just east of the mine dump. The lower interval, about 2 ft below the upper, is only about 1 ft thick and has been seen only in the outcrop just west of the mine dump. Individual columns average 6 to 8 inches in diameter although composite columns are larger in diameter. The longer columns are 3 to 4 ft in length (fig. 1). Cross sections range from circular to oval although flat sides frequently impart a polygonal aspect. In the upper interval, columns take form in the lower foot or so of disturbed beds. In general, small columns occur just above a basal, undisturbed unit of thin-bedded, gray, limestone and brown, silty limestone; the longer columns begin at slightly higher levels. A group of columns, separated by undisturbed beds on either side, has undisturbed beds below and a slightly arched massive bed of brown, silty limestone above. In the case of one particularly outstanding column (fig. 2), the lower end terminates at a bedding plane which is slightly deformed downward. Strata adjacent to the column, near the lower end, are also turned downward. Stratigraphically higher the beds marginal to the columns are markedly turned upward, and the immediately overlying layers are slightly domed. In this case, the column appears to have been pushed upward slightly so as to truncate adjacent beds; however, in numerous other examples, bedding planes may be traced across several columns (fig. 3). The latter relation shows that the columns were not formed by material moving upward from a basal mobile layer.

Certain structural details of the columns and intervening areas are particularly significant. Bedding planes within columns are highly arched upward, and a silty cap covers the upper end of many columns. Silty layers become thinner above individual columns and thicken in intervening areas. The columns consist almost entirely of gray limestone even though surrounding beds are interbedded limestone and silty limestone. These relations show that the columns were formed, as successive silty layers were thinned, by lateral migration of grains bringing the layers of limy mud together. Continued upward deformation arched the internal bedding planes and, in some cases, truncated marginal beds. In this way, beds above individual columns have been slightly arched and thinned. The columns in no way resemble algal structures but do resemble the columnar structures of limestone in western Montana, mentioned by Dorf and Lochman (1940, p. 545).

[1] Manuscript received October 23, 1958.

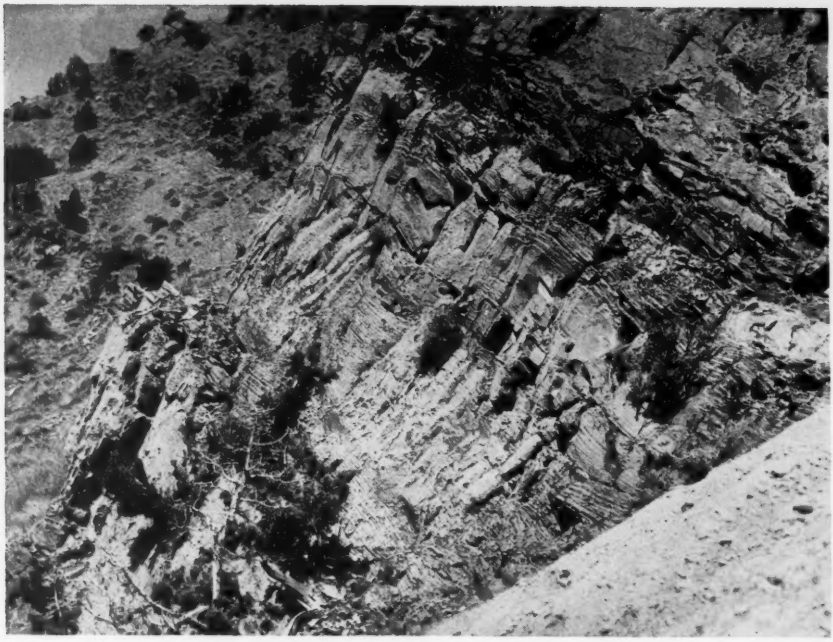

FIG. 1.—Columnar structures west of mine dump.

Factors, which have localized individual columns, remain obscure. The polygonal aspect of many columns first suggested that mud cracks might be involved; however, no indication of these features has been found. As already noted, strata overlying groups

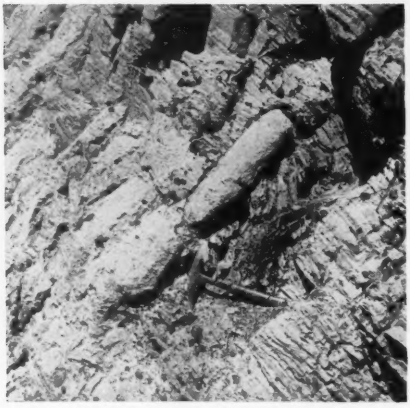

FIG. 2.—Column in foreground of figure 1.

FIG. 3.—Columns near center of figure 1.

of columns are arched upward slightly and those over the intervening undisturbed areas are depressed slightly. The relation suggests that downward movement in the intervening areas may have caused material of a basal mobile layer to rise at numerous loci in such a way that the immediately overlying silty layer was thinned above each. As this effect extended upward, successive overlying limy layers were forced together and columnar structures resulted.

REFERENCE

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POSSIBLE EDDY MARKINGS IN THE SHINARUMP CONGLOMERATE OF NORTHEASTERN UTAH[1]

J. KEITH RIGBY
Brigham Young University, Provo, Utah

Odd spiral markings from rocks of various ages and from various areas have been described and related to meandering worms or other crawling organisms. Recently a different type of spiraling impression in sandstone of the Triassic Shinarump conglomerate was discovered and photographed by Mr. Leo Thorne of Vernal, Utah. The markings are exposed in a small gully approximately 10 miles north of Vernal on the southern flank of the Uinta Mountains.

The spiral impression consists of numerous superimposed loops which are from one to three feet in diameter. These loops are cut approximately one-quarter to one-half of an inch into the sandstone bedding surface. Where successive loops overlap, small ridges or dams develop, indicating that the material was still plastic at the time of origin. In figure 1 the progression of the scriber was from right background toward the left foreground, with some retrograde motion. Chattering or vibratory movement of the scriber is shown by the rhythmically irregular pattern of the impression (fig. 2).

Origin of the impression is not certain. The author believes that it resulted from dragging of a small limb of a larger floating log caught in a vortex or eddy current of the stream which deposited the sandstone. It might have resulted from movement of a

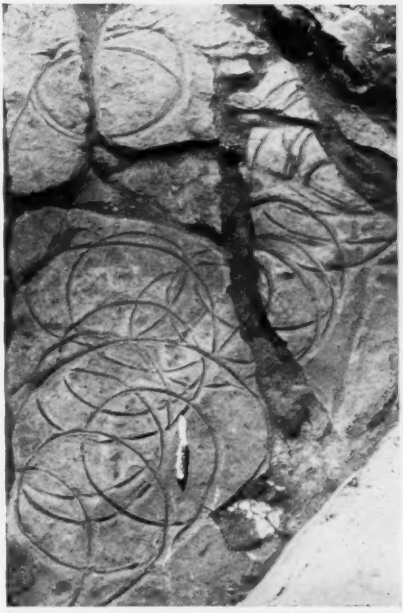

FIG. 1.—Bedding surface of Shinarump conglomerate inscribed by looped impressions thought to have resulted from dragging branches caught in a stream eddy current. Scale is shown by pocket knife. Photograph by Leo Thorne, Vernal, Utah.

[1] Manuscript received November 12, 1958.

pebble or stick caught in circular winds of a "dust devil" after the sands had been exposed along the stream bank but were still wet and plastic. There is little to suggest it might have been the result of life activities of an organism.

FIG. 2.—Details of impression showing pattern of overlap of loops and blocking of older loops by younger ones. Length of photograph represents a distance of two feet. (Photograph by Leo Thorne of Vernal, Utah.)

STATISTICAL STUDY OF HEAVY MINERALS IN SANDS OF THE SOUTH RIVER, AUGUSTA COUNTY, VIRGINIA: REVISION AND NOTES[1]

DOROTHY CARROLL
U. S. Geological Survey, Washington 25, D. C.

It was brought to my notice by Dr. R. D. Crommelin, Stichting voor Bodemkartering, Wageningen, Holland, that there seemed to be an error in the calculations given in table 6 of my paper describing a statistical study of sands from the South River, Augusta County, Virginia (Carroll, 1957). I had already noticed that there were a number of typographical errors in some of the tables. The paper as published was necessarily condensed because it contained a number of different analyses concerned with various aspects of the heavy mineral assemblages. The corrections given here do not invalidate the general results nor the methods of obtaining them.

The data for table 6 on page 397 of the original article have been re-calculated and corrected as shown in table 6, revised.

The F values resulting from the figures in table 6 and given on page 396 now read:

H (i) $A/B = 52.26/32.54 = 1.61$; $F_{.95}(1, 8) = 5.32$

H (ii) $B/C = 32.54/1.97 = 16.52^{**}$; $F_{.99}(8, 30) = 3.17$

The F value for (i) is not significant and the hypothesis is not rejected. Figure 4 illustrates this point. The F value for (ii) is highly significant at the 1 percent critical value of the F distribution (Dixon and Massey, 1951, table 7, p. 310–313) and the hypothesis is rejected. The geological implications of these tests are: (1) the weight of

[1] Publication authorized by the Director, U. S. Geological Survey. Manuscript received March 14, 1959.

TABLE 6, REVISED.—*Analysis of variance of heavy residue in the 0.12- to 0.06-mm grade*

Source	Degrees of freedom	Sum of squares	Mean square σ^2
(A) Between sides of main stream	1	52.26	52.26
(B) Between tributaries on a side	8	260.30	32.54
(C) Between samples within a tributary	30	59.18	1.97

the heavy residue being added from each side is not significantly different; and (2) the weight of the heavy residues is a significant property of the tributaries and can be used to differentiate one from another (see fig. 3).

I. (2a) *Frequency of occurrence of opaque grains (number percent) in the 0.12- to 0.06-mm grade* (p. 396)

The statement originally given here is a condensed account of the procedure used to obtain the analysis of variance from the data. In order to save space all the figures for counts were omitted.

The percent of opaque grains for each sample from tributaries on the north side is listed in table 2, and for the tributaries on the south side in table 3. The figures from which these are derived, namely the percent of opaque grains in each quadrant count for each sample from each locality, were used for the analysis of variance in table 7, p. 398. This analysis of variance tests the hypotheses which are described on pages 396 and 397. Correct statements of the observed F ratios are given below:

H (i) $F(1, 8) = 2.86$ NS

H (ii) $F(8, 30) = 4.0^*$

H (iii) $F(30, 80) = 5.7^{**}$

I. (2b) *Frequency of occurrence of zircon (number percent) in the 0.12- to 0.06-mm grade sands.* (p. 397)

The same condensed form of statement about the data for the zircon grains was used as for the opaque grains. Sections I. (2a) and I. (2b) should be similar. The analysis of variance for content of zircon is given in table 8, p. 398. See revised table 8, herewith.

The correct values for the F ratios are as follows:

H (i) $F(1, 8) = 0.01$ NS

H (ii) $F(8, 30) = 7.3^{**}$

H (iii) $F(30, 80) = 6.2^{**}$

The geological interpretation of the results of the analysis of variance is not altered by the errors in calculation of the F values.

I. (4) *Variation in frequency of occurrence of the different types of zircon in the 0.12- to 0.06-mm grade sands.* p. 398 and 399.

There are insufficient data given in table 4, p. 396, for calculation of analyses of variance of the different types of zircon. The analyses of variance were calculated from the counts for the slides, whereas the figures in table 4 are counts averaged for the 4 samples from each tributary. Recalculation of the analyses of variance for zircon types (1), (5), and (6) in table 9 (p. 399) gives the revised table 9.

There are some changes also in the interpretation of the results of table 9. *Zircon, Type 1* (well-rounded; polished or matt surfaces)

TABLE 8, REVISED.—*Analysis of variance of content of zircon (percent by number) in the 0.12- to 0.06-mm grade sands*

Source	Degrees of freedom	Sum of squares	Mean square σ^2
(A) Between sides of main stream	1	16.87	16.87
(B) Between tributaries on a side	8	12,559.63	1,569.95
(C) Between samples (slides) within a tributary	30	6,489.11	216.3
(D) Between quadrants (counts) within a slide	80	2,779.33	34.74

TABLE 9, REVISED.—*Analyses of variance of zircon types 1, 5, and 6 in the 0.12- to 0.06-mm grade sands*

Source	Degrees of freedom	Sum of squares	Mean square σ^2
ZIRCON (1)			
Between sides of main stream	1	2235.03	2235.03
Between tributaries on a side	8	2031.1	253.89
Between samples within a tributary	30	995.25	33.18
ZIRCON (5)			
Between sides of main stream	1	483.03	483.03
Between tributaries on a side	8	1015.20	126.9
Between samples within a tributary	30	1325.75	44.19
ZIRCON (6)			
Between sides of main stream	1	265.23	265.23
Between tributaries on a side	8	1528.8	191.1
Between samples within a tributary	30	949.75	31.66

$$H\ (i)\ F\ (1, 8) = 8.80^{**}$$
$$H\ (ii)\ F\ (8, 30) = 7.65^{**}$$

Zircon, Type 5 (grains with moderate wear)

$$H\ (i)\ F\ (1, 8) = 2.81\ NS$$
$$H\ (ii)\ F\ (8, 30) = 2.87\ NS$$

There is no significant difference between the two sides of the main stream or between the individual tributaries on a side. Such zircon is of little diagnostic value or interest in the heavy mineral assemblages as a whole.

Zircon, Type 6 (angular grains with very slight wear on the crystal faces)

$$H\ (i)\ F\ (1, 8) = 1.39\ NS$$
$$H\ (ii)\ F\ (8, 30) = 6.04^{**}$$

There is no significant difference between the two sides of the main stream for Type 6 zircon, but there is a highly significant difference between the individual tributaries. The remainder of this paragraph as it is printed on page 399 is correct.

II. (3a) *Quantity of opaque grains as a weight percent of the total heavy residue in the 0.12- to 0.06-mm grade sands.* p. 400.

Table 11 is correct. In evaluating the relation between the south side and the north side tributaries, the correct statement is:

$$F_{.995}(4, 4) = 23.2 \text{ and not } F_{.995}\ (1, 8) = 14.7.$$

There is a highly significant difference at the 1 percent level. Recalculation of variance between the north-side and south-side tributaries omitting the large contribution of tributary 12 gives:

$$F = \frac{0.0446}{0.036} = 1.24\ NS$$
$$F_{975}(3, 4) = 9.98,$$

showing that there is no significant difference (at the 5 percent level) of the weight of opaque grains contributed by these tributaries on either side of the main stream.

This result can be inferred from geological observation and it is interesting to find that the statistical analysis strengthens the geological observation.

II. (3b) *Quantity of zircon grains as a weight percent of the total heavy residue in the 0.12- to 0.06-mm grade sands.* p. 400.

Table 13 on page 401 has been correctly calculated. The relation between the contribution of the north-side and south-side tributaries (p. 400) is:

$$F = \frac{0.1487}{0.0073} = 19.8^{*}$$
$$F_{.975}(4, 4) = 9.60.$$

There is a significant difference at the 5 percent level between the weight of zircon added from either side.

It is hoped that the interpretations of the statistical evaluation of the data in the

original paper will help geologists to use statistics in heavy mineral studies. The study points the way to a more rigorous use of the facts obtained from grain counts.

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REVIEW

Clays and Clay Minerals, Fifth National Conference on Clay and Clay Minerals. Edited by Ada Swineford, 1958. Pp. vii +360 pages, 158 figs., 60 tables; $6\frac{1}{4} \times 9\frac{1}{4}$ in. Cloth. National Academy of Science-National Research Council Publication no. 566, Washington. Price $4.50.

The papers presented in the annual proceedings of the Fifth National Conference on Clays and Clay Minerals upholds the excellent quality of papers presented at the preceding four meetings. This conference was sponsored by the Committee on Clay Minerals of the National Academy of Science-National Research Council and the University of Illinois. The meeting was held at the University of Illinois on 8, 9, and 10 of October, 1956, and was organized by a local committee under the chairmanship of Dr. William F. Bradley.

Just a cursory glance at the Index to the publication will indicate that the papers presented include data on geology, mineralogy, crystallography, soil physics, physics, colloidal chemistry, ceramics, and allied branches and fields. It, therefore, is impossible to review each paper. An itinerary of a field trip to the locality of the famous Fithian illite is included and 27 papers are presented by 44 authors. Seventeen papers deal primarily with properties of clay minerals, i.e., clay-water systems, clay-organic systems, thermal properties, ion exchange, surface area determinations, plasticity, etc. and ten papers are concerned primarily with the origin, distribution, and occurrence of clay minerals.

In most cases each paper presents new data and ideas that may be classified under several headings. In the following list of subjects, the number in the parentheses indicates the number of papers presenting information about that subject:

1. Clay-water systems (4),
2. Clay-organic systems (4),
3. Thermal properties and high temperature phases (3),
4. New techniques and laboratory procedures (6),
5. Clay mineral lattices and structures (10),
6. Origin of clay minerals (9),
7. Occurrence of clay minerals (7),
8. Clays in soils (3),
9. Clay minerals and diagenesis (3).

This publication is a very welcome addition to the growing literature on clays and clay minerals.

JOHN B. DROSTE
Indiana University

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 29, NO. 2, p. 288
JUNE, 1959

ANNOUNCEMENTS

CALL FOR PAPERS TO BE PRESENTED AT 1960 ANNUAL MEETING OF SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS

The Annual Meeting to be held in Atlantic City on April 25–28, 1960, will include the following programs:

(1) RESEARCH COMMITTEE SYMPOSIUM, "Paleontological and Mineralogical Evidence for Polar Wandering and Continental Drift"; 1 day.
Chairman: A. C. Munyan, Sohio Petroleum Company, P.O. Box 2558, Billings, Montana.

(2) PALEONTOLOGY AND STRATIGRAPHY; 1 day.
Chairman: P. Tasch, Department of Geology, University of Wichita, Wichita, Kansas.

(3) MINERALOGY AND SEDIMENTARY PETROLOGY; 1 day.
Chairman: A. L. Kidwell, Jersey Production Research Corporation, Tulsa, Oklahoma.

Readers are encouraged to submit titles and abstracts (up to 350 words) for papers submitted for scheduling on the programs. Papers by non-members of S.E.P.M. must be sponsored by a Society member. The deadline for titles and abstracts is October 1, 1959. Please submit them directly to the appropriate program chairman, as listed above.

EIGHTH NATIONAL CLAY CONFERENCE

The Eighth National Clay Conference will be held on October 12, 13, and 14, 1959, on the University of Oklahoma campus at Norman, Oklahoma under the auspices of the Clay Minerals Committee of the National Academy of Sciences—National Research Council.

A field trip will be arranged for either Sunday, October 11 or Thursday, October 15, probably to the Wichita Mountains in southwest Oklahoma to visit clay occurrences of geological interest.

Two symposia of invited papers will be held on the subjects of "Clay-Water Systems" and "Clay Mineral-Geochemical Prospecting Methods." In addition to these special symposia there will be general sessions of contributed papers. All those having contributions should contact Professor C. G. Dodd, Chairman, Eighth National Clay Conference, University of Oklahoma, Norman, Oklahoma. The title and a letter of intent should be sent in by June 20, and a 250 word abstract by July 1.

Further information and a preliminary announcement of the Conference may be obtained by writing Professor Dodd.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 29, NO. 2, PP. 289–309
FIGS. 1–5, JUNE, 1959

SOCIETY RECORDS AND ACTIVITIES

REPORTS AND MINUTES OF THE THIRTY-THIRD ANNUAL MEETING OF THE SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS

The thirty-third annual meeting of the Society of Economic Paleontologists and Mineralogists was held in the Dallas Memorial Auditorium, Dallas, Texas, March 16–19, 1959, in conjunction with the annual meeting of The American Association of Petroleum Geologists.

The Society's program consisted of papers on Concepts of Stratigraphic Classification and Correlation; Paleontology and Stratigraphy; and Sedimentary Minerology and Petrology.

At a joint session on Tuesday morning, March 17, Gordon Rittenhouse, President of the S.E.P.M., presented the following address:

THERE IS A REASON

Mr. Chairman, fellow members of S.E.P.M and A.A.P.G, and guests, if I were a preacher instead of a geologist, I might take for my text today the words "There is a reason." I am not a preacher, of course, but as some of you know, I have been somewhat of a missionary within our profession for a way of thinking about rocks—or if you wish, a philosophy about how to look at rocks. This philosophy or way of thinking is not new—certainly it is not original with me but antidates by far my entrance into the field of geology some 30 years ago.

What is this way of thinking—this philosophy? It is based on the assumption that rocks as they occur today did not just happen, but that there is a reason for their being what they are and where they are. What rocks are and where they are is due to a combination of physical, chemical, and biological factors that have acted through time according to definite laws. These factors have left their imprints on the rock in varying degrees and, from these imprints or clues, the past history of the rock may be reconstructed with varying degrees of success. This reconstruction of the total history of the rock is to me of paramount importance. To do it one needs not only to observe and ask "why"; one must believe "There is a reason."

This may seem quite simple—something that we all do—and therefore you may be wondering why I am talking about it today. It is simple—but it certainly is *not* something we all do.

Let me illustrate this with two examples. I keep on my desk a piece of core that I call my "Separator of Men from Boys." I have given many budding geologists fresh from more than a score of universities a hand lens and knife and asked them to study this core for a few minutes and then to describe it, to give the rock a name, and to indicate what geological history can be deduced from it. I have found few "Men" and many "Boys." Less than half recognized that information about the relief, the climate, and the kind and age of rocks in the source area can be deduced from the kind and size of pebbles, or that size, sorting, and rounding of the pebbles suggest a relatively short distance of transport and deposition under fluvial conditions, probably in an alluvial fan.

Fewer than one in ten recognized that the orientation of the pebbles indicates that the beds are almost vertical, or that low porosity, close packing, and the kinds and number of contacts between pebbles indicate extensive post-depositional modification. Most of those young geologists were not asking themselves "What properties does this rock have that will tell where it came from, how and under what environmental conditions was it formed, and how has it been changed since it was deposited?" Nor were they saying "There is a reason" why it is like it is today.

As a second example, I might point to descriptions of measured sections. In publications these commonly read "sandstone, brown, fine-grained, cross-bedded, 14 feet," and I have no reason to believe the descriptions are more extensive in many field notebooks. Here we have major lithology, color, size of grain, and the presence of a primary structure. For distinguishing this bed from

those above and below, or for comparing it or the beds in a sequence, with beds in another measured section this may appear to be adequate, in fact, may appear to be a first very necessary step. But is it adequate? From the terms "sandstone" and "fine-grained" it may be inferred that the agent of deposition was a current of moderate velocity. What kind of current and what was its direction of flow? I submit that these are important questions to answer, since the answers may bear on selection of where to measure the next section or how the lithologic variations between sections are to be explained. In our example, cross-bedding may be a useful clue. But what do we know from just the word "cross-bedded"? Our answer may come from the direction of dip of the cross-beds, their inclination, their thickness and lateral extent, and their relation to beds above and below.

I might follow this example further, using the lack of information on composition conveyed by the broad term "sandstone" and the lack of information on how much induration has occurred and what caused the induration. I hope, however, that I have made my point; namely, that it is common to overlook may clues that could be used in reconstructing the history of rocks because we are not wondering what they mean nor assuming that "There is a reason."

In looking at any rock we have some purpose—and a limited time in which to achieve that purpose. Therefore we cannot describe everything—we must be selective, observing or measuring those features of the rock that will permit us to accomplish our purpose. In making this selection we are guided by our past experience—and by our way of thinking about rocks.

When our objective is limited, such as in identifying a subsurface structural datum, our choice may be easy, because our past experience or that of others may indicate what to look for. Generally little thought is required to identify the datum—although much thought may be needed to interpret what the position of the datum means.

When our objective is broader, the choice may be more difficult, requiring a combination of past experience and a way of thinking about rocks. Thus in our "sandstone, brown, fine-grained, cross-bedded, 14 feet" example, reliance is being placed on past experience but this time with the *hope* of accomplishing the purpose, experience having shown that useful geological interpretations may be made in some cases if vertical and lateral variations in lithology are known. Outlining lithologic geometries may be a powerful tool, particularly in subsurface work—provided enough control points are available to define the geometry and provided we know what the geometry means when we have it. Commonly our control is not adequate, and how we interpolate between control points to outline the geometry will depend on our way of thinking about rocks.

All too often, past experience is substituted for thought—not made its partner. Because certain types of observations or measurements have contributed to the successful solution of problems in the past, they are selected and applied indiscriminately to new problems. Here we have one type of "shot gun" approach, based on a philosophy which, in effect, says "If we can make enough observations on enough rocks, put them in a machine and turn the crank, something useful may come out." To some, this is the "modern statistical approach" to geological problems. This maligns statistical methods—which can be valuable in geology—though not as a substitute for thinking. Since this approach does not reach the objective in a minimum of time, if at all, it is wasteful of time, manpower and money. I prefer the "There is a reason" philosophy.

In selection of features that may be significant in rocks, we are faced with ever increasing knowledge in geology and related sciences, and ever increasing specialization. In looking at rocks and at problems involving rocks there is an increasing tendency to look at specialized aspects of the rock, rather than at the rock as whole. The sands "belong" to one specialist; the clays, the carbonates, the isotopes, the trace elements and various fossil groups, to others. Specialization has great potentialities for our science, since it can lead to a better understanding of the physical, chemical, and biological factors that have made rocks what they are today. But it has great hazards as well. Let's not forget how the elephant appeared to the three blind men—like a wall, like a post, like a snake. Just as we need to consider the en-

tire elephant, we need to consider the entire rock—putting each type of observation and deduction in its proper perspective.

With an increasing number of things to observe or measure, it becomes increasingly important to make the proper choice—the choice that will permit us to reach our objective in the time available. To me the obvious procedure is to go from the simple to the complex, from the rapid to the slow, from the less expensive to the more expensive. In general, but not always, this will mean going from the large to the small, from the visible to the invisible, from the direct to the indirect. There is no magic formula, no "gimmick," that will indicate what to look for or when. This will depend on the problem, the purpose, the time, the material available, and the way one thinks about rocks. Because I am firmly convinced that what rocks are and where they are has resulted from a combination of physical, chemical, and biologic factors that have acted through time according to definite laws, and that those factors have left their imprints on the rock in varying degrees, I believe that as we study rocks we should observe, ask "why" and remember "There is a reason." Thank you.

HENRYK B. STENZEL
Honorary Membership

Also, at the joint session on Tuesday morning, President Rittenhouse presented an honorary membership award to Henryk B. Stenzel, a past-president of the Society. The award consists of a certificate and the receipt of both of our *Journals* for life.

Dr. Stenzel was born February 7, 1899, in Pabianice, Poland. His formal education was received at Schlesische Friedrich Wilhelms Universitaet, at Breslau, Germany, where he was granted a Ph.D. degree in 1922. For two years after his graduation, he was an assistant at the Geological Insitute of the University at Breslau. He then came to the United States and to the Agricultural and Mechanical College of Texas where he was an instructor and later was promoted to assistant professor. He remained here from 1925 to 1934, at which time he accepted a position with the Bureau of Economic Geology at the University of Texas, Austin, serving in this capacity for twenty years. For seven years during this period he also taught geology at the University, holding the title of "Professor of Geology." From 1954 to 1957 he was "Special Professor of Geology" at the University of Houston.

Dr. Stenzel's publications include articles on tectonics of intrusive granite bodies, areal geology, tertiary stratigraphy and paleontology, decapod crustacea, and fossil ostreidae. He holds membership in many professional organizations, among them: Geological Society of America (Fellow), Paleontological Society (member, president in 1955), American Association of Petroleum Geologists (member, served on Business Committee, Medal Award Committee, and Research Committee), and the Malacological Society of London.

In 1929 Dr. Stenzel joined the S.E.P.M. He served as its Secretary-Treasurer from 1939 until 1949 when he was elected President of the Society.

Dr. Patrick H. Monaghan was the recipient of the first award to be presented by the S.E.P.M. for a "Best Paper at the Convention." President Rittenhouse presented him with a book of his choice, *The Oceans*, for his

DR. PATRICK H. MONAGHAN
Best Paper at 1958
Los Angeles Convention

paper, "The Solubility of $CaCO_3$ in Salt Water," presented at the 32nd Annual Meeting of the Society in Los Angeles. His paper was judged, by a committee of five, on content, organization, originality, and presentation.

Now senior research engineer, production research division of the Humble Oil and Refining Company of Houston, Texas, Dr. Monaghan was born July 25, 1922, in Memphis, Tennessee. He received a B.S. degree in chemical engineering from Louisiana Polytechnic Institute in 1943; in 1949 he was awarded a master's degree in chemistry from Louisiana State University and a Ph.D. degree was conferred upon him by the same University in 1950.

Dr. Monaghan was a Radar Officer with the U. S. Marine Corps from 1943 to 1946, at which time, upon his discharge, he became associated with the Sperry Gyroscope Company as field engineer. In 1947 he entered L.S.U. Graduate School to work toward his doctorate in chemistry. He has been employed by Humble since 1950.

A number of chemical publications by Dr. Monaghan have appeared in *Analytical Chemistry*. In addition to the paper which is the subject for this award, Dr. Monaghan published an article in the S.E.P.M.'s Quarterly Journal, the *Journal of Sedimentary Petrology*, entitled, "The Origin of Calcareous Ooliths" (Volume 26, Number 3).

Dr. Monaghan became an associate member of the S.E.P.M. in 1955. He is also a member of the American Chemical Society and The American Institute of Mining, Metallurgical and Petroleum Engineers.

In addition to the above awards, S.E.P.M. Research Committee Chairman, Grover E. Murray, presented the Society's Award for the Best Paper for 1957 in the *Journal of Paleontology* to Helen Tappan and Alfred R. Loeblich, Jr., husband-wife team, for their paper entitled, "Correlation of the Gulf and Atlantic Coastal Plain Paleocene and Lower Eocene Formations by Means of Planktonic Foraminifera," which appeared in the November issue, Volume 31, Number 6. Dr. Murray also presented the award for the Best Paper for 1957 in the *Journal of Sedimentary Petrology* to Raymond Siever, for his paper entitled, "Pennsylvanian Sandstones of the Eastern Interior Coal Basin," published in the September issue, Volume 27, Number 3.

The Best Paper Awards are the fifth to be presented by the S.E.P.M. They consist of a certificate given to the author whose paper, appearing in the Journals during the second preceding year, is judged by the Research Committee to be the most outstanding contribution of the year.

Born in Birmingham, Alabama, on August 15, 1914, Dr. Loeblich attended Oklahoma University where be obtained both B.S and M.S. degrees in geology (1937 and 1938 respectively). A year after receiving his Ph.D. degree from the University of Chicago, in 1941, Dr. Loeblich entered the U. S. Army as a Field Artillery Captain, serving in the New Hebrides, Okinawa, and Philippine Islands. Upon his discharge in 1946, Dr. Loeblich became associate curator of Invertebrate Paleontology and Paleobotany at the U. S. National Museum in Washington, D. C., where he remained until 1957 when he accepted his present position at California Research Corporation.

Loeblich has published over 50 articles on foraminiferal faunas, morphology and taxonomy, bryozoa, and stratigraphy in the *Journal of Paleontology, A.A.P.G. Bulletin, Micropaleontology, Bulletin of American Paleontology, U. S. National Museum Bulletin*, and many others.

In addition to his membership in the S.E.P.M., Dr. Loeblich is a member of The American Association of Petroleum Geologists and the Paleontological Society. He is a fellow in the Geological Society of America, Cushman Foundation for Foraminiferal Research, and the Washington Academy of Science. He is also a member of numerous foreign professional organizations, Sigma Xi, and Phi Beta Kappa.

Dr. Loeblich was appointed a member of S.E.P.M.'s Research Committee in 1957, serving as vice-chairman for that year. His three-year term on this committee will expire with the annual meeting in Dallas, in 1959.

Mrs. Alfred R. Loeblich (who publishes under the name of Helen Tappan) was born in Norman, Oklahoma, October 12, 1917. She, also, received B.S. and M.S. degrees in geology from the University of Oklahoma, and in 1942 was awarded a Ph.D. degree from the University of Chicago.

For one year prior to her connection with the U. S. Geological Survey in 1943, Mrs. Loeblich was an instructor in geology at Tulane University. In 1952 she was engaged in the study and collection of foraminifera in Western Europe (John Simon Guggenheim Foundation). From 1954–1957, just prior to her California connections, Mrs. Loeblich was an Honorary Research Associate in Paleontology at the Smithsonian Institution in Washington, D. C.

Mrs. Loeblich's general field of publication is foraminiferal faunas, morphology, classification and correlation. In addition to many articles in the *Journal of Paleontology*, she has published in the *Bulletin of American Paleontology, Journal of the Washington Academy of Science, U. S. National Museum Bulletin, Micropaleontologist*, and others.

Mrs. Loeblich is a fellow of the Geological Society of America, and a member of the Paleontological Society and the Cushman Foundation for Foraminiferal Research, in addition to membership in Sigma Xi and Phi Beta Kappa.

MR. AND MRS. ALFRED R. LOEBLICH, JR.
BEST PAPER AWARD, 1957
Journal of Paleontology

Raymond Siever, born September 14, 1923, in Chicago, Illinois, obtained B.S., M.S. and Ph.D. degrees in geology from the University of Chicago, the latter being conferred in 1950.

From 1943–1944, Mr. Siever was Research Assistant in the Coal Division for the Illinois Geological Survey. In 1944, and serving until 1946, Mr. Siever joined the photogrammetry unit of the U. S. Army Air Force, returning to the Illinois Survey in 1947 where he worked as assistant geologist, associate geologist, and geologist in the Coal Division. His work consisted of research in stratigraphy, coal and sedimentary petrology. From 1956 to 1957, when he became associate professor of geology at Harvard, Dr. Siever was National Science Foundation Senior Postdoctoral Fellow at Harvard University.

Dr. Siever's publications include articles on stratigraphy, sedimentary petrology,

RAYMOND SIEVER
BEST PAPER AWARD, 1957
Journal of Sedimentary Petrology

coal petrology and structure. These have been published in the *Journal of Sedimentary Petrology*, *Bulletin of The American Association of Petroleum Geologists*, *Journal of Geology*, and *Illinois Geological Survey Reports*.

In addition to active membership in the S.E.P.M., Dr. Siever is a fellow of the Geological Society of America and The American Association for the Advancement of Science. He is a member of The American Association of Petroleum Geologists, Society of Economic Geologists, and Sigma Xi.

Dr. Siever was a member of the S.E.P.M. Research Committee from 1954 to 1957. He was chairman of the committee in 1956 and organized a Symposium presented at the Chicago, 1956, Convention entitled, "Directional Properties of Sedimentary Rocks."

ANNUAL BUSINESS MEETING

The annual business session of the Society was called to order at 1:30 P.M., Tuesday, March 17, by Gordon Rittenhouse, President, who introduced the officers for the new year as follows: President, Samuel P. Ellison, Jr.; Vice-President, William J. Plumley; Secretary-Treasurer, John Imbrie; Editors of the *Journal of Paleontology*, M. L. Thompson and Charles W. Collinson; and Editor of the *Journal of Sedimentary Petrology*, Jack L. Hough.

It was moved, seconded, and carried that the minutes of the 1958 meeting be approved as published in the June, 1958, *Journal of Sedimentary Petrology* and the July, 1958, *Journal of Paleontology*.

The following reports were not presented at the Business Meeting, but instead they are printed in full below.

1. *Report of the Editors of the Journal of Paleontology (M. L. Thompson and C. W. Collinson).*—Volume 32 of the *Journal of Paleontology*, issued in conjunction with the Paleontological Society, contains 1170 pages of text and 148 plates. The S.E.P.M. portion of the volume contains 418 pages of text and 39 collotype plates of fossil illustrations. This represents a decrease of about 20 pages of text and two plates from the preceding volume. A larger part than in some previous volumes are without full tone plates. The subject matter covered concerns many fields of paleontology and can be referred in a general way to about 18 papers on megafossils and 12 papers on microfossils. Several papers can be defined as of both types, and a few papers concern mixed faunas. Paleoecology is the principal subject of four papers. Three papers deal mainly with biostatistics, and two are about biochemistry. Seventeen of the papers concern faunas of Paleozoic age, and 14 papers concern fossils of Mesozoic and Cenozoic ages. Many phyla of invertebrate animals, as well as some plants, are discussed to some degree in this volume.

Approximately the same number of unpublished manuscript pages and plates are on hand as were on hand at this time last year.

The editors wish to report that the comprehensive Index of the first 25 volumes of the *Journal of Paleontology* has come to a waiting stage until the species-genera portion of the Index has been completed. The subject-author portion of the Index is in manuscript form, and all of the species-gen-

S.E.P.M. COUNCIL, OUTGOING AND INCOMING

Sitting, left to right: Jack L. Hough, Editor *Journal of Sedimentary Petrology*; Raymond E. Peck, Secretary-Treasurer; Gordon Rittenhouse, President; W. M. Furnish, Vice-President; M. L. Thompson, Co-Editor *Journal of Paleontology*. Standing: William J. Plumley, Vice-President-Elect; Samuel P. Ellison, Jr., President-Elect; John Imbrie, Secretary-Treasurer-Elect; Charles W. Collinson, Co-Editor *Journal of Paleontology*.

era part is completed except for that from Volume 8.

We call attention to the fact that we have recently appointed associate editors in compliance with the recommendation given at the last meeting of the 1957 Council. Dr. Robert H. Shaver of the Indiana Geological Survey and Dr. Alan B. Shaw of the Shell Oil Company have generously consented to serve.

The Illinois Geological Survey furnished secretarial, technical, and financial assistance.

2. *Report of the Editor of the Journal of Sedimentary Petrology (Jack L. Hough).*—*The Journal of Sedimentary Petrology* was published in 1958 as Volume 28, Numbers 1 through 4. A summary of the contents is given in the accompanying table. The December issue, Number 4, was expanded by 16 pages in order to keep the wait for publication within a period of nine months. This temporary expansion was accomplished without exceeding the printing budget. The supply of unpublished manuscripts has increased somewhat during 1958, and it may be necessary to consider further expansion of size of the *Journal* during 1959. The national origins of the articles, notes, and discussions of Volume 28 were as follows:

United States	44
England	7
Canada	2
Wales	1
New Zealand	1
India	1
Netherlands	1
France	1
Czechoslovakia	1

As in the past nine years, the University of Illinois has provided the services of the Editor and of a part-time editorial assistant.

3. *Report of the Secretary-Treasurer (Raymond E. Peck).*—Income for 1958 was $1,845.14 more than in 1957 due largely to increase in income from subscriptions to *Journal of Paleontology* and *Journal of Sedimentary Petrology*—the price of *Journal of Sedimentary Petrology* was raised in 1958 and there was an increase in membership dues to persons taking this *Journal*.

Sale of back numbers amounted to $5,026.55. This is a primary source of income. This was a decrease from 1957 but subscriptions more than made up the difference.

Operating costs decreased $424.99 this

Journal of Sedimentary Petrology, Vol. 28, 1958

	Articles		Notes		Discussions		Reviews		S.E.P.M. Data[1] Pages	Advertising[2] Pages	Other[3] Pages	Total Pages
	No.	Pages	No.	Pages	No.	Pages	No.	Pages				
1. (Mar.)	14	105	1	3	—	—	—	—	15	1	4	128
2. (June)	10	94	4	7	1	2	7	5	14	1	5	128
3. (Sept.)	13	115	2	3	—	—	1	2	3	1	4	128
4. (Dec.)	11	121	1	2	2	5	—	—	—	2	8	144
Total	48	435	8	15	3	7	8	7	32	5	21	528

[1] Including announcements of meetings, programs, minutes of annual meeting, and membership list.
[2] Exclusive of advertisements on covers.
[3] "Other" includes title pages, index, errata, and announcements.

past year so we operated in the black to the extent of $2,270.13—an unusual circumstance in this day and age. I believe Dr. Ellison reported a profit of $907.46 last year.

Much credit for operating in the black is due to the editors of the *Journal of Paleontology*—their expense was $2,400 less than in 1957. Our thanks to Drs. Thompson and Collinson.

On December 31, 1958, our balance in the bank was $30,118.76—this included $8,062.37 in the Publication Fund. About half of this money in the Publication Fund will be used in paying for *Silica in Sediments*.—This has just been published and we hope the Society will make money on it.

Special Publications have continued to make money—all except the Index to the

MEMBERSHIP, MAILING, AND JOURNAL STATISTICS

	Dec. 31, 1958	*Dec. 31, 1957*	*Dec. 31, 1956*
1. S.E.P.M. Membership:			
Active Members	1094	1085	990
Associates	351	319	292
Correspondents	6	6	5
Honorary Members	5	3	3
	1456	1413	1290
2. *Journal of Paleontology* Mailing List:			
S.E.P.M. Active & Honorary Members	503	528	509
S.E.P.M. Associates	167	160	150
Subscribers	912	840	810
P.S. Members	649	638	624
	2231	2166	2093
3. *Journal of Sedimentary Petrology* Mailing List:			
S.E.P.M. Active & Honorary Members	726	721	677
S.E.P.M. Associates	220	207	184
S.E.P.M. Correspondents	6	6	5
S.E.P.M. Subscribers	997	979	890
	1949	1913	1756
4. Edition of *Journal of Paleontology*	2500	2400	2400
5. Edition of *Journal of Sedimentary Petrology*	2500	2400	2100
6. Number of Pages, *Journal of Paleontology*	1170	1190	1394
7. Number of Plates, *Journal of Paleontology*	148	150	146
8. Number of Pages, *Journal Sedimentary Petrology*	528	484	386
9. New Members	125	150	137
10. Transfers to active membership	24	49	41
11. Members and associates dropped for non-payment of dues (1/1/59)	65	49	17

The Council, Society of Economic Paleontologists and Mineralogists:

We have examined the accompanying balance sheet of Society of Economic Paleontologists and Mineralogists at December 31, 1958, and the related statement of income and surplus for the year then ended. Our examination was made in accordance with generally accepted auditing standards, and accordingly included such tests of the accounting records and such other auditing procedures as we considered necessary in the circumstances.

In our opinion, the statements mentioned above present fairly the financial position of Society of Economic Paleontologists and Mineralogists at December 31, 1958, and the results of its operations for the year then ended, in conformity with generally accepted accounting principles applied on a basis consistent with that of the preceding year.

ARTHUR YOUNG & COMPANY

Tulsa, Oklahoma, January 19, 1959

SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS
BALANCE SHEET, DECEMBER 31, 1958

ASSETS

	Total	*General Fund*	*Publication Fund*
CURRENT ASSETS:			
Cash	$33,366.90	$25,304.53	$ 8,062.37
Savings account	2,823.01	2,823.01	—
Accounts receivable	295.40	230.40	65.00
Total current assets	$36,485.31	$28,357.94	$ 8,127.37
PUBLICATIONS:			
Journal of Paleontology:			
Issues prior to 1958—10,374 journals at $0.50 each (1,592 complete volumes)	$ 5,187.00	$ 5,187.00	$ —
Issues 1 to 6 of 1958—1,486 journals, at cost	2,984.63	2,984.63	—
Reprints in 1948, Volume 1, 1927—656 volumes, at cost	1,427.28	1,427.28	—
Journal of Sedimentary Petrology:			
Issues prior to 1958—4,069 journals at $0.50 each (1,103 complete volumes)	2,034.50	2,034.50	—
Issues 1 to 4 of 1958—2,068 journals, at cost	2,249.56	2,249.56	—
Special publications:			
Turbidity Currents, 108 copies, at cost	92.35	—	92.35
Recent Marine Sediments, 464 copies, at cost	957.46	—	957.46
Finding Ancient Shorelines, 86 copies, at cost	150.31	—	150.31
Regional Aspects of Carbonate Deposition, 327 copies, at cost	729.99	—	729.99
Journal of Sedimentary Petrology Index, 1,494 copies, at cost	862.49	—	862.49
Total publications	$16,675.57	$13,882.97	$ 2,792.60
FURNITURE AND FIXTURES (less reserve, $1,793.84)	$ 1.00	$ 1.00	$ —
DEFERRED CHARGES	$ 2,085.50	$ 873.05	$ 1,212.45
	$55,247.38	$43,114.96	$12,132.42

LIABILITIES AND SURPLUS

CURRENT LIABILITIES:			
Accounts payable	$ 4,011.13	$ 2,798.68	$ 1,212.45
Amount payable to Paleontological Society	3,371.57	3,371.57	—
Total current liabilities	$ 7,382.70	$ 6,170.25	$ 1,212.45
DEFERRED CREDITS:			
Subscriptions to Journals—net of portion to be received by Paleontological Society	$ 9,456.19	$ 9,456.19	$ —
Membership dues for 1959	9,071.00	9,071.00	—
Total deferred credits	$18,527.19	$18,527.19	$ —
SURPLUS, per accompanying statement	$29,337.49	$18,417.52	$10,919.97
	$55,247.38	$43,114.96	$12,132.42

Journal of Sedimentary Petrology. We have sold approximately 600 copies of it to date and have 1400 copies on hand. We are in the RED on it at present.

Mr. Dott is exploring the possibility of reprinting back numbers of both *Journals.* There is considerable call for those numbers which are out of print and we hope Mr. Dott will work out a deal that will continue to make money for the Society.

Membership shows a net gain of 43 persons. We added 125 new members last year

SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS
STATEMENT OF INCOME AND SURPLUS
YEAR ENDED DECEMBER 31, 1958

	Total	General Fund	Publication Fund
INCOME:			
Membership dues and subscriptions:			
Journals of Paleontology and Sedimentary Petrology	$ 4,777.00	$ 4,777.00	$ —
Journal of Paleontology	16,979.26	16,979.26	—
Journal of Sedimentary Petrology	13,145.54	13,145.54	—
	$34,901.80	$34,901.80	$ —
Sales of special publications:			
Turbidity Currents	$ 304.88	$ —	$ 304.88
Recent Marine Sediments	805.00	—	805.00
Finding Ancient Shorelines	472.70	—	472.70
Regional Aspects of Carbonate Deposition	911.30	—	911.30
Journal of Sedimentary Petrology Index	751.75	—	751.75
	$ 3,245.63	$ —	$ 3,245.63
Sales of back numbers:			
Journal of Paleontology, Volumes 1 to 31	$ 3,541.65	$ 3,541.65	$ —
Journal of Sedimentary Petrology	1,484.70	1,484.70	—
	$ 5,026.35	$ 5,026.35	$ —
Sales of plates	$ 538.66	$ 538.66	$ —
Advertising	$ 771.95	$ 686.95	$ 85.00
Donation from The American Association of Petroleum Geologists	$ 2,040.00	$ 2,040.00	$ —
Miscellaneous	$ 334.44	$ 334.44	$ —
	$46,858.83	$43,528.20	$ 3,330.63
Less portion of 1957 income accrued to Paleontological Society	3,427.71	3,427.71	—
	$43,431.12	$40,100.49	$ 3,330.63
COSTS AND EXPENSES:			
Cost of printing:			
Journal of Paleontology	$12,224.64	$12,224.64	$ —
Journal of Sedimentary Petrology	10,342.07	10,342.07	—
Journal of Sedimentary Petrology Index	1,179.98	—	1,179.98
	$23,746.69	$22,566.71	$ 1,179.98
Expenses:			
Clerical salaries	$ 7,755.00	$ 7,755.00	$ —
Office supplies	499.41	499.41	—
Postage and express	1,602.90	1,602.90	—
Office rent	2,000.00	2,000.00	—
Telephone	47.70	47.70	—
Audit fee	211.08	211.08	—
Payroll taxes	161.70	161.70	—
Miscellaneous	2,002.06	1,880.76	121.30
	$14,279.85	$14,158.55	$ 121.30
Adjustment for (increase) decrease in inventory of publications	$ (478.88)	$ (899.38)	$ 420.50
	$37,547.66	$35,825.88	$ 1,721.78
NET INCOME	$ 5,883.46	$ 4,274.61	$ 1,608.85
SURPLUS AT DECEMBER 31, 1957	23,454.03	14,142.91	9,311.12
SURPLUS AT DECEMBER 31, 1958	$29,337.49	$18,417.52	$10,919.97

as against 150 during 1947. We have dropped 44 members and 21 associates (total 65) for non-payment of dues. We dropped only 48 at the end of 1957.

We have lost 8 members through death during the past year.

The *Journal of Paleontology* mailing list has increased by 65 and the *Journal of Sedimentary Petrology* list by 36 during the past year.

4. *Report of the Research Committee* (*Grover E. Murray, Chairman*).—Membership of the committee, with terms ending at the annual meeting of each year as indicated, is:

1959	*1960*	*1961*
Virgil Barnes	H. A. Ireland	Heinz A. Lowenstam
R. V. Hollingsworth	Grover E. Murray	Arthur C. Munyan
A. R. Loeblich, Jr.	W. D. Pye	F. B. Van Houten
D. L. Inman	L. M. Cline	W. H. Akers
Stuart Levinson	S. G. Wissler	
Haydn H. Murray		

At the annual meeting in St. Louis on April 1, 1957, the committee selected "Concepts of Stratigraphic Classification and Correlation" as the topic for the 1959 annual symposium. W. C. Bell and L. L. Sloss were subsequently requested by chairman Murray to serve as co-chairmen in arranging this program. The symposium was organized during 1957–1958 as follows:

Session I

Presiding:
Grover E. Murray, Chairman of Research Committee
Arthur C. Munyan, Vice-Chairman

Hollis D. Hedberg (Gulf Oil Corporation, Pittsburgh, Pennsylvania), The Classification Controversy

John Rodgers (Yale University, New Haven, Connecticut), The Meaning of Correlation

Harry E. Wheeler (University of Washington, Seattle, Washington), Stratigraphic Units in time and Space.

Taras P. Storey (Husky Oil & Refining Limited, Calgary, Alberta, Canada) and J. R. Patterson (Amerada Petroleum Corporation, Calgary, Alberta, Canada), Stratigraphy-Traditional and Modern Concepts

Harold L. James (U.S.G.S., Washington, D. C.), Problems of Stratigraphy and Correlation of Precambrian Rocks with Particular Reference to the Lake Superior Region

A. D. Cumming, J. G. C. M. Fuller (Saskatchewan Department of Mineral Resources, Regina, Saskatchewan, Canada), and J. W. Porter (Canadian Superior Oil Company of California, Regina, Saskatchewan, Canada), Separation of Strata: Paleozoic Limestones of the Williston Basin

Session II

Presiding:
W. C. Bell, University of Texas
L. L. Sloss, Northwestern University

James L. Wilson (Shell Development Company, Houston, Texas), North American Cambro-Ordovician Biostratigraphy—Layer Cake Geology

Digby McLaren (Geological Survey of Canada, Ottawa, Ontario, Canada), The Role of Fossils in Defining Rock Units in the Devonian of Western and Arctic Canada

Keith Young (University of Texas, Austin, Texas), Techniques of Mollusk Zonation in the Texas Cretaceous

John A. Wilson (University of Texas, Austin, Texas), Mammalian Biostratigraphic Zones in the Continental Tertiary

C. O. Durham, Jr. (Louisiana State University, Baton Rouge, Louisiana), Provincial Time-Rock Nomenclature in the Gulf Cretaceous, Help or Hindrance?

Frank E. Lozo (Shell Development Company, Houston, Texas), Cyclic Correlation Units in the Texas Comanche Cretaceous

At the annual meeting in Los Angeles, March 10, 1958, the committee nominated Henryk B. Stenzel for Honorary Membership and recommended his election by the council. Subsequently this nomination was approved by the council and Dr. Stenzel was notified of his election by President Rittenhouse.

During 1958, the members of the committee were polled by mail regarding additional nominations for Honorary Membership and for Correspondents. Although no official nominations were made up to the time of the annual meeting, a list of prospective nominees was developed.

The best paper in the *Journal of Paleontology* for 1957 was selected, in a closely contested vote, to be that by Alfred R. Loeblich, Jr. and Helen Tappan entitled *Correlation of the Gulf and Atlantic Coastal Plain Paleocene and Lower Eocene Formations by Means of Planktonic Foraminifera*, November, 1957. The paper by Raymond Siever entitled *Pennsylvanian Sandstones of the Eastern Interior Coal Basin*, September, 1957, was selected as the best paper in the 1957 *Journal of Sedimentary Petrology*. Awards for these papers were presented to the respective authors by the chairman at the annual meeting in Dallas, Texas.

5. *Report of the Publications Committee (Samuel P. Ellison, Jr., Chairman).*—The Publications Committee, consisting of Samuel P. Ellison, Jr., Chairman (1959), Grover E. Murray, ex-officio member (1959), H. A. Ireland (1959), and T. H. van Andel (1960) considered one manuscript (*Modern Ecology*

of Foraminifera by Fred B. Phleger) during the past year. The manuscript was recommended as acceptable for a special publication provided the estimated possible sales would be profitable. It was finally decided that potential sales would not pay for the publication and the manuscript was released to the author.

6. *Report on the Earth Sciences Division of the National Research Council* (*John C. Frye, S.E.P.M. Representative*).—In accordance with its primary responsibility, the Division during the year rendered advisory services to federal agencies through ten committees and conducted one conference, all upon request of the government. About 80 scientists took part in this work.

The Arctic Sea Ice Conference was held February 24–27, 1958. The Division is preparing the papers and discussions for publication. The Committee on Waste Disposal, Advisory to the Atomic Energy Commission, published its report to the Reactor Development Division, AEC, as NAS-NRC Publication 519. During the year a meeting of this committee with representatives of the petroleum industry, as well as of AEC, was held in the Academy Building in Washington.

The Committee on the Glacial Map of the United States, east of the Rockies, has completed compilation of the map to be published by the Geological Society of America. A proof copy of the map was on display at the annual GSA meeting in November.

The Committee on Clay Minerals held its seventh annual conference in Washington, D. C., October, 1958, and the volume resulting from the sixth conference will be published by Pergamon Press in its monograph series on the earth sciences. The Committee on the Measurement of Geologic Time issued its last annual report covering the year 1954–55 as NAS-NRC Publication 500, and the Committee was discharged with thanks for having seen its work through to successful completio

Seven fellowship committees were active during the year; six groups screened applicants for awards under programs supported by the National Science Foundation, the Fulbright Act, and the Smith-Mundt Act, and one group met to evaluate candidates for a special award administered by the American Chemical Society.

The Division's Annual Meeting, attended by Francis J. Pettijohn, the outgoing S.E.P.M. Representative, formed part of the first general meeting of the entire membership of the National Research Council. The Research Council met as a body on March 30 and 31 and, after the introductory discussion of five major problems facing science in America and a survey of Academy-Research Council activities bearing on these problems, the membership divided itself into five sections for specific discussions. The findings will serve as guidance for continuing activities of the Council and of the Earth Sciences Division.

7. *Report on the American Geological Institute* (*Gordon Rittenhouse*).—S.E.P.M. was represented at meetings of the Board of Directors of A.G.I., held at the 1958 A.A.P.G.-S.E.P.M. and G.S.A. meetings in Los Angeles and St. Louis. Since many of the activities of the Institute are reviewed in *GeoTimes*, which is sent to all S.E.P.M. members, only the following items of special interest are reviewed here.

a. Finances remain a critical problem. Support of A.G.I. by the geological societies is on a year-to-year basis, and a proposed reduction in support by the G.S.A. has emphasized the uncertainty of even the present operations, which for 1959 will approximate $81,000. Grants aggregating $210,000 earmarked for the Earth Sciences Register, an International Abstract Survey, and Russian Translations have been obtained from the National Science Foundation. Additional grants, totaling $135,000, for geological abstracting, a visiting scientist program, and other projects are pending. The grants do not help support the general operations of A.G.I., which the Executive Director believes should be about $140,000–150,000 per year. No solution of the problem of providing A.G.I. a stable, predictable income has been reached.

b. In an effort to help the finances of A.G.I., Robert Karpinski of the Chicago Undergraduate Division of the University of Illinois conceived the idea of a "Committee of 1000 for A.G.I." in which less affluent members of the profession, who could not afford to join the Committee of 100, could

contribute $10 to A.G.I. The Board of Directors authorized the Executive Committee to form a "Committee of 1000 for A.G.I." for 1959. Such contributions would be for the year unless the individual wished to continue.

c. During the past year A.G.I. prepared and distributed more than 15,000 copies of a new career booklet "Shall I Study the Geological Sciences?" and published "Earth for the Layman" and a second edition of "Directory of Geological Information." Beginning in 1959, A.G.I. will publish "Geo-Science Abstracts" which will replace "Geological Abstracts," publication of which is being discontinued by G.S.A.

d. Following receipt of NSF grants totaling $140,000, a Russian Translation Center, managed by Dr. R. W. Fairbridge, has been set up just off the campus of Columbia University. Work is proceeding on translation of the Russian abstract journal, *Referativnyi Zhurnal*, the *International Geology Review*, and two books, Nalivkin's "Facies Studies," and Belousov's "Fundamental Problems in Tectonics." The *International Geology Review* is expected to appear in January, 1959; the two books about mid-1959. The translation project is described in some detail in the October, 1958, issue of *GeoTimes*.

8. *Report of the S.E.P.M. Representative to the A.G.I. Government Relations Committee (Norman S. Hinchey).*—Several members of the A.G.I. Government Relations Committee met on November 7, 1958, in St. Louis, Missouri. The new chairman was unavoidably prevented from being present and Robert C. Stephenson, executive director of A.G.I., presided informally in his absence.

Topics which were discussed briefly included: proposed rules for fossil collecting on federal lands, presented by S.V.P.; a proposed geophysical research institute in Hawaii; travel reimbursement for government scientists serving non-profit organizations as distinguished lecturers, etc.; a suggested proposal to found a minerals research institute; and licensing and registration.

9. *Report of the Joint Committee on Invertebrate Paleontology (Raymond C. Moore).*—Chief accomplishment on the Treatise project during 1958 has been completion of the volume on Trilobitomorpha (mainly trilobites) with an accompanying introduction to the phylum Arthropoda and description of the nontypical jointed-leg invertebrates classed as Protarthropoda. This volume (Part O) will contain approximately 570 pages and very numerous illustrations. It is the work of 18 contributing authors from six countries and because of complex division of the work for preparation of systematic descriptions, as well as the unsettled nature of numerous problems of classification, unusual difficulties have been encountered. Work now is finished except for offset printing and binding.

Prospectively the next published Treatise volume will be Part I (Mollusca 1), which is planned to include the chitons, scaphopods, and Paleozoic gastropods. Final editorial work on this unit is in progress and type setting is about to begin. Work also is actively under way to complete organization of Part Q (Arthropoda 3) on ostracodes and it is possible that at least one or two other units may be made ready for press during 1959. Unhappily, no definite statement yet can be made as to the probable time of publication of Part C (Foraminifera), even though it had been expected that this unit would have been completed before 1958. Major sections of the typescript have not yet come into hands of the editor, although some divisions have been completed long ago.

10. *Report of S.E.P.M. Representative on Council of A.A.A.S. (Robert B. Neuman).*—I attended the meeting in Washington, D. C., in December, 1958, as the S.E.P.M. member of the Council of the A.A.A.S. These conclaves are unique in this country in bringing together scientists (and science teachers) in many fields with the obvious danger of cross-fertilization. Thus the Section E program on the history of geology brought together science historians as well as geologists. Section L (History of Science) continued the theme with a program of papers on Darwin. Other programs with papers of special interest to me and my paleontological associates were given by the Society of Systematic Zoology (in Section F), and the Dentistry Section (a Symposium on calcification in Geological Systems) to name two. There were several others. This kind of program together with the broad educational aspects of A.A.A.S., and the fact that the A.A.A.S. is playing a large part in organ-

izing the International Oceanographic Congress in New York in September, 1959, (another example of its interdisciplinary functions) seem to me to warrant continued affiliation of the S.E.P.M. with the A.A.A.S.

11. *Report of the Permian Basin Section (Carl Ulvog).*—The fourth annual meeting will be held at the Desert Aire Motel in Alamogordo, New Mexico, on April 16, 1959. Registration for this meeting is scheduled to begin the afternoon of April 15. Mr. M. R. Stipp is general chairman. A most interesting technical session is being arranged under the supervision of Mr. R. F. Meyer, program chairman.

A field conference in the Sacramento Mountains will follow the business and technical meeting, being slated for April 17 and 18. Arrangements will be made for registering during the afternoon of April 15 and all day April 16, at the Desert Aire Motel, Alamogordo, New Mexico. The field conference is sponsored jointly by the S.E.P.M., Permian Basin Section, and the Roswell Geological Society. Chairmen are Carl Ulvog and Frank Packard. The field trip will be confined to the west slope of the Sacramentos and will be under the general leadership of Dr. Lloyd C. Pray.

Officers elected for 1958 were: J. P. D. Hull, Jr., President; Carl Ulvog, 1st Vice-President; M. Russell Stipp, 2nd Vice-President; Edward R. Kennedy, Secretary; and Roy Harris, Treasurer. Mr. Hull subsequently resigned from his position and Mr. Ulvog is completing his term. Since March 1, 1959, is the deadline for ballots to be returned, the 1959 executive committee cannot be named at this time.

The Midland group is planning a series of evening meetings, the first of which will be held on January 28. It is hoped that these meetings will arouse greater interest and activity in our organization. Membership is steadily increasing, having now reached a total of 433, of which 12 may be considered as residing completely outside of the Permian Basin Area.

12. *Report of the Gulf Coast Section (Marcus A. Hanna).*—The past year, 1957–58, under the Presidency of Jack Collie, continued the success of preceding years.

The Gulf Coast Section jointly with the Houston Geological Society held a field trip December 6 under the leadership of Fred Smith, Professor of geology at Texas A. & M. College. The field trip committee consisted of E. H. Rainwater, chairman, C. W. Stuckey, Jr., H. G. Schoenike, H. B. Stenzel, and L. J. Vittrup. It was assisted by many other individuals. The trip covered the "Upper and Middle Tertiary of Brazos River Valley, Texas." Although the weather was cold some 275 individuals made the one day trip. The field trip guide book is available through the Houston Geological Society.

The annual meeting of the section was held in Corpus Christi, Texas, October 27 through 29, 1958. The first day of the two-day Technical Session was a joint meeting with the Gulf Coast Association of Geological Societies. The second day, the section held its own technical session concurrently with the other meeting. Several interesting papers were presented.

The annual business meeting followed the technical session with President Jack Collie presiding. Reports of the officers and committee chairmen were presented. Accomplishments and anticipated activities of several projects were discussed.

President Collie thanked his officers and the members for their cooperation during the year. The incoming president talked a few moments after which the meeting adjourned.

Many of the members were a part of the group of near 100 which attended the field trip October 30 through November 1 in a study of "Sedimentology of South Texas."

13. *Report of the Pacific Section (Charles W. Cary).*—The Pacific Section has an active paid-up membership of 140, and a balance in the treasury of $1,948.66. President of the Section is Charles W. Cary and Secretary-Treasurer is Alvin A. Almgren.

This year, National and Pacific Section S.E.P.M. membership awards and subscriptions to both *Journals* were granted to eighteen students from various Pacific Coast Colleges and Universities. The faculty of the Paleontology or Geology Department of each school nominated the student to receive this award.

The monthly Biostratigraphy Seminar, sponsored jointly by the Pacific Section S.E.P.M. and the Bakersfield College, is in

progress. Eight papers by distinguished research workers from the West Coast, covering the field of stratigraphy, paleontology, and ecology, are being presented. Mr. Stan Carlson is chairman, and the average attendance at the meetings is approximately fifty.

The S.E.P.M. Pacific Section sponsored their annual dinner meeting and field trip on April 24 and 25. Dr. Earl Brabb is chairman of the event and will be assisted by Dr. Weldon Rau. The Geology and Paleontology of exposures in the vicinity of Boulder Creek, Santa Cruz Mountains, California, will be studied. Dr. Brabb will present a paper on the Stratigraphy of the Boulder Creek Area at the Friday evening dinner preceding the field trip.

The Pacific Section S.E.P.M. will again cooperate with the A.A.P.G. and S.E.G. in putting on the Thirty-Sixth Annual Fall Meeting at Los Angeles on November 12 and 13. A two-day technical session and dinner meeting are being planned by Dr. Weldon Rau, program chairman.

A dinner dance will be held in December which is co-sponsored by the S.E.P.M.—A.A.P.G.—S.E.G. On the committee representing S.E.P.M. will be Richard L. Brooks.

14. *S.E.P.M. President's Report* (*Gordon Rittenhouse*).—The financial condition of the Society continues to improve. The General Fund showed a profit of $4,274.61 as compared with a profit of $907.46 in 1957 and a loss of $637.17 in 1956. The Publications Fund showed a profit of $1,608.85 as compared with $4,101.77 in 1957 and $1,860.88 in 1956. These figures are not all "cash," since inventory of our publications and other factors are taken into consideration in arriving at these figures.

The improved status of the General Fund is due in part to the increase in dues that became effective in 1958 and in part of lower than anticipated costs of publication of the Society's two journals. The editors of the two journals are to be highly commended for their efforts in holding down costs, as well as for continuing their usual efficient handling of the two publications. The smaller profit on the Publications Fund was due partly to the *Journal of Sedimentary Index* remaining a "loss" item and partly to much smaller income from sales of "Carbonate Deposition" which was published in 1957.

Membership in the Society has increased only slightly during the past year and numbered 1456 on December 31, 1958, as compared with 1413 on December 31, 1957. Because of the adverse economic situation during the year, no special effort toward increasing membership was made. A need for such efforts has been discussed with President-Elect Ellison who has acted to appoint a Membership Committee.

The Research Committee under the chairmanship of Grover Murray organized a symposium on "Concepts of Stratigraphic Classification and Correlation" for presentation at the Dallas meeting. The subject "Relationship of Paleontology and Mineralogy to Polar Wandering and Continental Drift" was selected for the symposium at the 1960 meeting at Atlantic City. Arrangements for this program, which is being organized under the direction of Arthur Munyan, vice-chairman, are largely completed. The 1958 symposium entitled "Silica in Sediments" is appearing early in 1959 as a S.E.P.M. Special Publication.

Because there is a very limited pool of the members eligible for nomination for president, a special committee composed of H. B. Stenzel, F. J. Pettijohn, and R. R. Shrock, chairman, was appointed to consider the whole problem of how and from whom to choose the president. The recommendations of this committee will be presented to the council and members for consideration.

I wish to extend my sincerest gratitude to the many members of the Society who have served as officers, editors, representatives, and committee members during my term of office.

It was moved, seconded, and carried that the By-Laws be changed to read as follows:

Article III, Section 1. Nominations for officers shall be made in the following manner. Prior to September 1 of each year, the president shall designate a nominating committee to consist of not less than five members none of whom shall be members of the council, instructing this committee to submit two nominations for president, vice-president, and secretary-treasurer, and nominations for editors of the two Journals,

these nominations to be in the secretary's hands before September 15. If desired, this committee may nominate two slates of candidates for editor of one or both of the Journals.

Article VIII, Section 1. The president and the past-president shall be directors of the American Geological Institute, the past president being the senior director. They shall represent the Society on said Institute. The term of office as directors shall begin at the fall meeting of the American Geological Institute following assumption of their office and shall terminate two years later; provided that this provision in no way extends their terms of office as members of the council of the Society.

It was moved, seconded, and carried that a referendum vote (in the form of a mailed ballot) be taken to determine whether the Society desires one or two slates of officers.

The meeting was turned over to incoming President Samuel P. Ellison, Jr., who called for a report of the Resolutions Committee.

The Resolutions Committee, composed of F. T. Connolly (chairman), Lynn Jacobsen, and J. Robert Moore, III, presents the following "Resolutions of Thanks."

BE IT RESOLVED THAT in behalf of the Society we extend an expression of our sincere thanks to the following:

TO WILLIAM M. FURNISH, technical program chairman, for his general supervision and handling of the technical program;

TO JAMES E. BROOKS, S.E.P.M. vice-chairman, for his capable attention to the many details of the meeting;

TO GROVER E. MURRAY, chairman of the Research Committee, together with W. C. BELL and L. L. SLOSS, for preparing the Research Symposium, "Concepts of Stratigraphic Classification and Correlation";

TO JULES BRAUNSTEIN and ALFRED G. FISCHER for arranging the papers on mineralogy and sedimentary petrology, and on paleontology and stratigraphy;

TO W. DOW HAMM, general chairman, WILLIAM B. HEROY, general vice-chairman, ROBERT E. RETTGER, A.A.P.G. program chairman, and to the chairmen and members of all the convention sub-committees, for their efforts in the organization of the Dallas convention;

TO THE EXECUTIVE COMMITTEE of the A.A.P.G., for appropirating $2,000.00 as office rent for the Society Headquarters at Tulsa;

TO ROBERT H. DOTT, for his continued guidance as Business Manger of the S.E.P.M.;

TO OUR EDITORS—M. L. THOMPSON, CHARLES W. COLLINSON, and JACK L. HOUGH, for their untiring efforts in the time-consuming job of editing our publications, the *Journal of Paleontology* and the *Journal of Sedimentary Petrology*;

TO ROBERT R. SHROCK and BARBARA H. BLOOM for the preparation of the Index to the *Journal of Sedimentary Petrology* and to JACK L. HOUGH for editing that volume;

TO H. A. IRELAND for editing our Special Publication Number 7, *Silica in Sediments*;

TO DANIEL A. BUSCH and PHILIP H. SCRUTON, for designing the book plate to be used for the award for the Best Paper Presented at the Convention;

AND TO THE STATLER HOTEL, for providing excellent convention headquarters facilties.

The meeting adjourned at 2:15 P.M.

CONSTITUTION AND BY-LAWS

(AMENDED, 1958 AND 1959)

SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS

A DIVISION OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

CONSTITUTION

ARTICLE I. NAME

The Society shall be known as the Society of Economic Paleontologists and Mineralogists.

ARTICLE II. OBJECT

The object of the Society shall be to promote the science of stratigraphy through research in paleontology and sedimentary petrology, especially as these relate to development of knowledge of the geology of petroleum.

ARTICLE III. MEMBERSHIP

1. The Society shall be composed of active members, associate members, honorary members, correspondents, and patrons.

2. Active members shall be persons engaged in paleontologic, petrographic, or stratigraphic studies as applied to the geology of petroleum and who have been duly elected active members, juniors, or associates in The American Association of Petroleum Geologists.

Active and honorary members only shall be known as members.

3. Associate members shall be known as associates. Any person engaged in paleontologic, petrologic, or stratigraphic studies that have application to the geology of petroleum is eligible for associate membership. Associates shall enjoy all the privileges of membership in the Society, save that they shall not hold office, sign applications for membership, or vote.

4. Honorary members shall be persons of distinguished achievement whose contributions to paleontology, petrology, and stratiggraphy have an application to the geology of petroleum.

5. Correspondents shall be persons not resident in North America who have made distinctive contributions to paleontology, petrology, and stratigraphy that have application to the geology of petroleum.

6. Patrons shall be persons who have bestowed important favors on the Society.

ARTICLE IV. OFFICERS

1. Executive authority of the Society is vested in a council consisting of six members, duly elected officers, as follows: president, vice-president, secretary-treasurer, the past-president, and the editor of each of the two Journals. The chairman and the vice-chairman of the Research Committee and the presidents of Regional Sections shall be non-voting members of the council.

2. The president shall discharge the usual duties of a presiding officer at all meetings of the Society and council.

3. The vice-president shall assume the duties of the president in case of his absence.

In the event of the absence from the meetings of both president and vice-president, the duties of presiding officer shall fall upon one of the other members of the council in the following order: past-president, secretary-treasurer.

4. The secretary-treasurer shall keep records of the proceedings of the Society, and a complete list of the membership. He shall attend to the preparation and mailing of notices and other materials required in the business of the Society. The secretary-treasurer shall have custody of all funds of the Society, and shall keep a detailed account of receipts and disbursements.

5. The council shall consider all nominations for membership and pass on the qualifications of the applicants; may elect honorary members, correspondents, and patrons; shall have control and management of the affairs and funds of the Society; shall determine the manner of publication and pass on the material presented for publication; and shall designate the place of the annual meeting. In the event of a tie vote among the voting council, the president, vice-president, and secretary-treasurer's votes shall prevail. The council is empowered to establish a business headquarters for the Society and to

employ such persons as are needed to conduct the business of the Society.

6. Elections shall be held annually to select a president, vice-president, secretary-treasurer, and the editors.

ARTICLE V. MEETINGS

1. The Society shall hold at least one stated meeting a year, which shall be designated as the annual meeting. The time and place of the annual meeting shall be designated by the council, but in general, it shall be held in connection with the annual meeting of The American Association of Petroleum Geologists.

2. The annual meeting shall be devoted to the reading and discussion of scientific papers, to the transaction of Society business, and other appropriate functions.

3. The program for the annual meeting shall be arranged by the council, or under its direction.

ARTICLE VI. SECTIONS

Local sections of the Society may be established according to provisions of the by-laws.

ARTICLE VII. AMENDMENTS

The constitution may be amended by a two-thirds vote of returned mail ballots received by the secretary-treasurer sixty days after proposal of amendments with provision for vote is mailed to the membership; provided that the proposed amendment has been signed by at least twenty members, and provided further that the proposed amendment must first have the approval of the council and the executive committee of The American Association of Petroleum Geologists.

BY-LAWS

ARTICLE I. DUES

1. The fiscal year of the Society shall correspond with the calendar year.

2. The annual dues of members and associates of the Society who desire only the *Journal of Paleontology* shall be ten dollars ($10.00). The annual dues of members and associates who desire only the *Journal of Sedimentary Petrology* shall be seven dollars ($7.00). Members and associates may receive both Journals by the payment of seventeen dollars ($17.00). Members of the Society who are also members of the Paleontological Society and receive the *Journal of Paleontology* through the latter Society, may retain membership in the Society of Economic Paleontologists and Mineralogists by the payment of two dollars ($2.00) per year dues. The annual dues are payable in advance on the first day of each calendar year. A bill shall be mailed to each member and associate before September 1 of each year, stating the amount of annual dues and the penalty and conditions for default of payment. Members and associates who shall fail to pay their annual dues by January 1 shall not receive further copies of either Journal, nor shall they be privileged to buy Society publications at special discounts made to the membership, until such arrears are met.

3. The council may from time to time elect as honorary members, correspondents, and patrons, candidates who have been nominated by a majority vote of the research committee. A vote of four members of the council shall be required for election. Honorary members, correspondents, and patrons shall not be required to pay annual dues.

ARTICLE II. DUTIES AND PRIVILEGES OF MEMBERS

1. Members and associate members dropped for non-payment of dues may apply to the council for reinstatement, and, provided settlement is made of any outstanding indebtedness for publications and other charges approved by the council, may be reinstated by vote of four members of the council.

2. Members shall be eligible to receive publications of the Society at special subscription rates as authorized by the council or as provided in these by-laws.

3. The council is authorized to transmit without charge such publications as it may direct to honorary members, correspondents, and patrons.

4. Only active and honorary members shall have the right to vote in electing officers and in transacting the business of the Society.

ARTICLE III. OFFICERS

1. Nominations for officers shall be made in the following manner. Prior to September 1 of each year, the president shall designate a nominating committee to consist of not less than five members none of whom shall be members of the council, instructing this committee to submit two nominations for president, vice-president, and secretary-treasurer, and nominations for editors of the two *Journals*, these nominations to be in the secretary's hands before September 15. If desired, this committee may nominate two slates of candidates for editor of one or both of the *Journals*.

2. Ballots containing the nominations for officers, alphabetically arranged under each office, shall be prepared by the secretary-treasurer and mailed to each member of the Society on or before October 1. Neither the ballot nor the enclosing envelope need contain the name of the voting member, but an outer envelope that contains the sealed ballot must bear the name of the voting member. The returned ballots received by the secretary-treasurer on or before December 1 shall be counted by him, and if requested, shall be submitted to recount by the council. A plurality of the votes received for any office constitutes election.

3. If, after his election by the regular ballot, the president shall not be able to discharge the duties of his office, because of death or resignation, the duly elected vice-president shall then assume the duties and title of president with all of the authority vested in him by the Constitution. In the event the vice-president shall not be able to assume said duties, then the succession shall be in the following order: past-president, secretary-treasurer. If none of the above mentioned members of the council shall be able to assume the office of the president, then a special election shall be held in which at least two qualified members, nominated by the council, shall be voted upon by the membership by means of a special mailed ballot. Any vacancies in the normally constituted council caused by such succession or for any other reason may be filled with a temporary appointment by the council.

4. Nominees for the office of president shall be active members in good standing, who shall have served (or may be serving concurrently at the time of nomination) as vice-president, secretary-treasurer, chairman of the Research Committee, or editor of one of the Society's official publications.

5. The vice-president shall be the officer of the council responsible for arrangements for the annual meeting, including selection of program chairmen, and shall keep in close contract with the Research Committee and others concerning technical papers and symposia to be presented.

ARTICLE IV. PUBLICATIONS

1. There shall be two editors, one for the *Journal of Paleontology* and one for the *Journal of Sedimentary Petrology*. The editors shall be in charge of editorial business of their respective Journals. Each shall submit an annual report of such business, shall have authority to solicit papers and material for such Journals, and may appoint associate or co-editors.

2. The *Journal of Paleontology* and the *Journal of Sedimentary Petrology* are designated as official publications of the Society. The council is not authorized to initiate and publish other periodicals.

3. A publication fund may be established consisting of an assignment of a portion of dues as designated by the council, and such donations as are specifically made for that purpose. The council is authorized to provide special publications from this fund as may be deemed desirable, and to fix terms for sale or other distribution of these publications.

ARTICLE V. FINANCIAL METHODS

1. No financial obligations shall be contracted without express sanction of the Society or council, but all ordinary incidental running expenses have sanction without special action.

2. Statements of accounts charged to the Society, other than miscellaneous running expenses, shall be approved by the president before the secretary-treasurer pays the amount out of funds of the Society not otherwise appropriated, and the receipted bill shall be held as the secretary-treasurer's voucher.

3. The secretary-treasurer shall have charge of the financial affairs of the Society and shall annually submit reports as secre-

tary-treasurer covering the fiscal year. He shall receive all funds of the Society, and, under the direction of the council, shall disburse all funds of the Society. He shall cause an audit to be prepared annually by a public accountant at the expense of the Society. He shall give a bond, and shall cause to be bonded all employees to whom authority may be delegated to handle Society funds. The amounts of such bonds shall be set by the council and the expense shall be borne by the Society. The funds of the Society shall be disbursed by check as authorized by the council.

ARTICLE VI. BUSINESS REPRESENTATIVES

The president and the secretary-treasurer of the Society shall act as business representatives of the Society in the business committee of The American Association of Petroleum Geologists. These representatives shall conduct such business with the executive committee of the Association as is of mutual interest to the Society and the Association in the interims between the annual meetings of the Society and the Association. Approval of the action of these representatives on the part of the Society during any year is reserved to the council in session at the annual meeting at the close of that year. Questions remaining unsettled between the representatives of the Society and the executive committee of the Association shall be considered in a joint meeting of the council of the Society or its authorized representatives and the executive committee of the Association at the annual meeting of the Association at the close of the interim period during which such questions have arisen.

ARTICLE VII. SECTIONS

1. The establishment of local sections of the Society may be authorized by unanimous vote of the council approving a petition for such establishment signed by ten members of the Society. Such local sections may elect officers, conduct meetings, and engage in other scientific activities.

2. The council is authorized and directed to withdraw the charter of any established local section if there is evidence that it has become inactive.

ARTICLE VIII. DIRECTORS OF AMERICAN GEOLOGICAL INSTITUTE

1. The president and the past-president shall be directors of the American Geological Institute, the past-president being the senior director. They shall represent the Society on said Institute. The term of office as directors shall begin at the fall meeting of the American Geological Institute following assumption of their office and shall terminate two years later; provided that this provision in no way extends their terms of office as members of the council of the Society.

2. In the event of a vacancy by resignation, death, or other causes among the two directors who represent the Society on said Institute, the president of the Society shall nominate a director from the ranks of active members of the Society, and this director shall complete the unexpired term.

ARTICLE IX. REPRESENTATIVE ON NATIONAL RESEARCH COUNCIL

At the expiration of each three-year term, the president shall appoint a representative on the National Research Council to serve for a term of three years.

ARTICLE X. RESEARCH COMMITTEE

1. The objectives and duties of the Research Committee shall be to foster and encourage research; to advise the Society and council on research activities which may concern the Society, or which may be recommended or initiated under its sponsorship; to develop a symposium for the annual meeting if so requested; to select recipients for Best Paper Awards each year for each Journal; to nominate candidates for honorary members, correspondents, and patrons; and to deal with any other matters referred to it from time to time by the president or the council.

2. The activities of the Committee shall be directed by a chairman and a vice-chairman, to be appointed by the president, with the approval of the council, from the active members of the Committee. The term of the appointment of the chairman shall be one year. The vice-chairman will normally succeed the chairman the following year. In the event either of these offices is vacated for any reason, the council shall appoint a

qualified replacement for the unexpired term.

3. Membership of the Committee shall be appointed by the president from members and associates of the Society. The Committee shall consist of fourteen members, but this total may be changed at the discretion of the council. Two committee members, preferably one paleontologist and one mineralogist, shall be chosen from each of several geographic regions to be selected by the council. In addition, advisory members may be appointed from foreign areas. The terms of appointment of members and advisory members shall be for three years. Appointments shall be staggered, with the junior member from any region serving at least one year with the senior member from that region. If vacancies develop on the Committee the president shall make suitable appointments for the unexpired term.

ARTICLE XI. PUBLICATIONS COMMITTEE

1. The membership of this committee shall consist of five members, including a chairman, three other members, and the chairman of the Research Committee as an ex-officio member. The tenure of office of the chairman and members shall be two years. Membership of the committee shall be appointed by the president from members and associates of the Society.

2. The duties of the Publications Committee shall be to recommend to the council manuscripts or symposia which merit consideration as S.E.P.M. special publications. The Publications Committee shall further recommend type of reproduction, number of copies, and cost figures of manuscripts or symposia.

3. Upon approval of the council, this committee, with the appropriate Society editor or editors, shall edit (or have edited), and publish these manuscripts or symposia.

4. The activities of this committee will include recommending to the council suggestions for improving the quality of our Society *Journals* consistent with the budgeted monies allotted for publication.

ARTICLE XII. AMENDMENTS

The by-laws may be amended at any annual business meeting by two-thirds vote of the members present, or by mail ballot sent to the members, in which case two-thirds of the returned ballots received in sixty days after mailing must approve the amendment in order to make it effective. Any proposed changes to the by-laws must first have the approval of the council.

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